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# FOREWORD

The 4th Weather Group has actively supported the USAF Aerospace Research Pilot's School (ARPS) at Edwards Air Force Base, California, since its inception in 1961. The information in this pamphlet has been compiled by Captain William R Jeffries III, of this group, and Rolf M Nilsestuen (Major, AFRes), for use as the basis of one of the lectures given to each class of the ARPS by Captain Jeffries on the environmental effects on aerospace systems.

Meteorologists who support the research, development, test, and evaluation of aerospace systems must also have a thorough understanding of the effects of the natural environment. Furthermore, this requirement for knowledge of natural environmental effects does not diminish when an aerospace system enters the operational phase. For these reasons, this pamphlet is being distributed to field units with the expectation that it will help achieve understanding of solar effects on the natural environment.

*Robert F. Long*  
ROBERT F LONG  
Colonel, USAF  
Commander

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A DESCRIPTIVE SUMMARY OF THE SUN, SOLAR PHENOMENA AND SOLAR-  
TERRESTRIAL RELATIONSHIPS

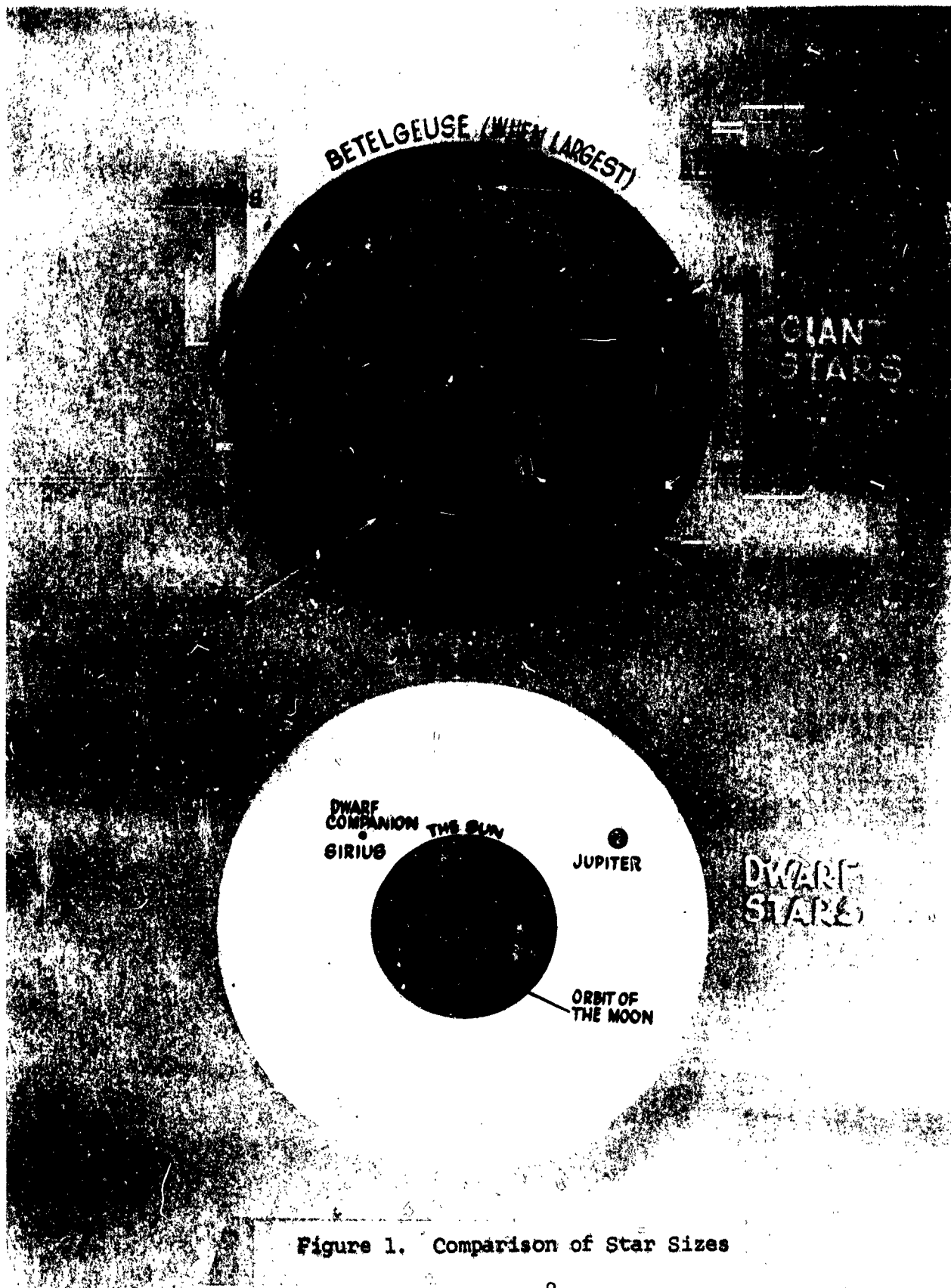
1. Introduction.

a. General Physical Description.

Our sun is a star--one of the billions of stars in the Milky Way galaxy, which is only one of many galaxies in our universe. It is a unique star to us, because it is the only one whose shape and surface can be seen. Our sun is relatively small in size (see Figure 1) and energy output compared with many stars in our own galaxy, but compared with terrestrial standards, its size and energy output defy comprehension.

The diameter of the sharp boundary of the sun's visible sphere is over a million kilometers ( $1.4 \times 10^6$  km) or about 110 times the earth's diameter. In illustration: if the earth-moon system were placed with the earth at the center of the sun (see Figure 1), the moon would be about half the distance out to the sun's surface. The mass of the sun is about  $2 \times 10^{33}$  grams (gm) or over three hundred million times more massive than the earth. The sun is entirely gaseous and composed largely of hydrogen (80%) and helium (19%). Despite this gaseousness, the density at the center of the sun approaches 100 grams per cubic centimeter ( $\text{gm/cm}^3$ ) while the overall mean density is only 1.4 times that of water. The mean distance between the earth and the sun is about  $1.5 \times 10^8$  kilometers. This distance is termed the "Astronomical Unit" or AU, which is more precisely equal to 149,566,500 + 500 kilometers (92,956,200 + 300 statute miles according to data from Mariner II [42]).

As seen from the earth, the sun requires about four weeks to rotate on its axis. However, it does not rotate like a solid body. This rotational period as seen from the earth is called the synodic or apparent period, and will vary rather smoothly from about 27 days at the solar equator to over 35 days near the solar poles. Another period of rotation occasionally referred to is the solar sidereal or actual period. This rotational period is slightly shorter than the synodic period, varying between 24.7 days at the solar equator and about 32 days at  $75^\circ$ . As an illustration of the difference between the synodic and sidereal rotation of the sun, consider Figure 2. In Figure 2a, a sunspot at the solar equator lies on a plane connecting the solar axis, the center of the earth, and some fixed star. 24.7 days later (Figure 2b), the sunspot has rotated once completely around the sun back to the plane connecting the sun's axis to the star. However, the earth has moved from point a to b in its



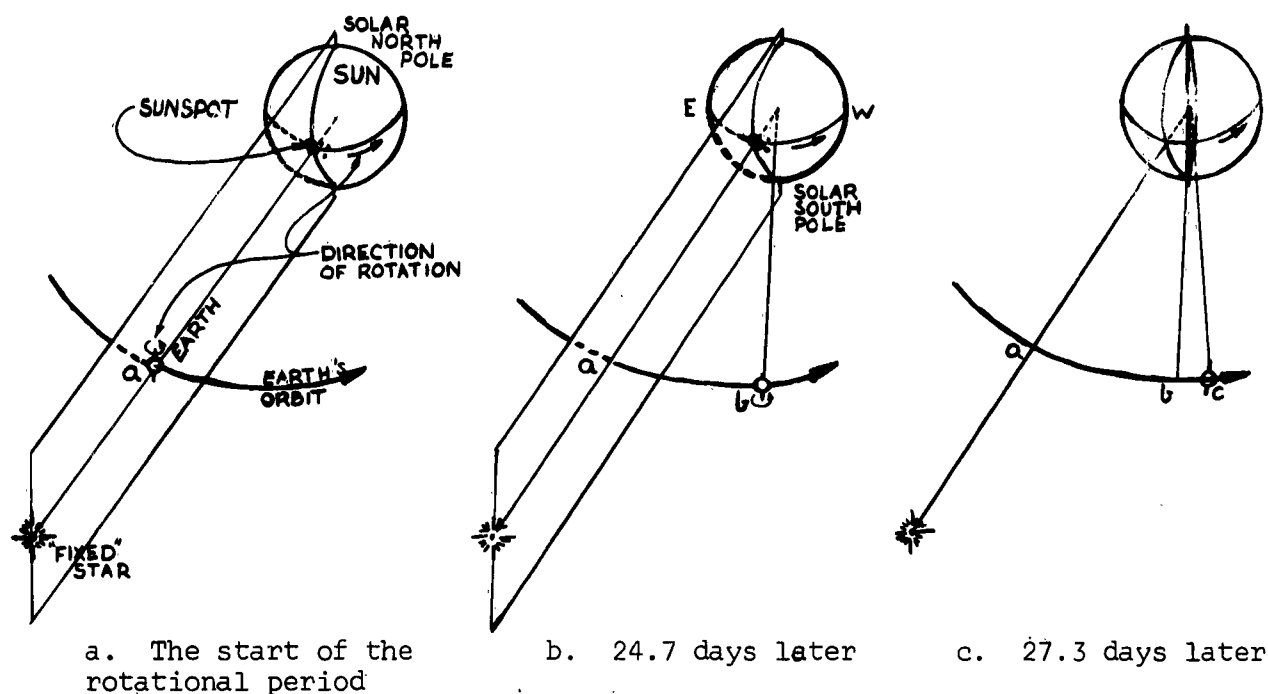


Figure 2. Illustration of Synodic and Sidereal Rotation of the Sun.

orbit during this time. Fig 2b illustrates the sidereal rotational period. A little more than two and a half days is required for the sunspot to catch up with a plane joining the axis of the sun with the center of the earth at point c (Figure 2c). This period of 27.3 days, depicted by Figure 2c, is the synodic solar rotational period, i.e. the apparent period required for a spot on the sun to rotate completely around the sun as viewed from the earth.

Although the various levels of the solar atmosphere will be discussed later, this is an appropriate place to mention a further curious fact of solar rotation. At any given latitude, as height above the photosphere (the visible surface of the sun) increases, the rotation period decreases. If the rotation at the equator is 27.3 days at the top of the photosphere, it is only about 23 days at the higher levels of the chromosphere (which can only be seen in monochromatic light; the higher level of the chromosphere usually being viewed in the light of ionized calcium) [10]. Thus, at the lower levels of the solar atmosphere, there is an eastward drift of material, whereas at higher levels there is a relative westward drift. The difference between these drifts decreases toward the poles. Thus the sun's rotation is very complicated, with various portions of the sun rotating at different speeds. The

reason why this happens is one of many things which are unsatisfactorily explained in solar physics. The direction of this rotation is from left to right as seen from the northern hemisphere of the earth (see Figure 2b). Thus, the solar features rise over the left limb which is designated east. One may easily orient east and west on the sun by remembering that if one is looking at the sun, the east solar limb is nearest the eastern horizon of the earth, and the west limb nearest the western horizon. North and south are determined similarly.

For billions of years the sun has been radiating energy at the rate of  $4 \times 10^{33}$  ergs per second (ergs/sec). The source of this energy lies deep within the sun, at the core, where the temperature is of the order of  $15 \times 10^6$  °K. The core has an estimated radius of about  $10^5$  km. It represents about 40 percent of the total mass of the sun and produces about 90 percent of the energy of the sun.

Surrounding the core is a zone of solar material in radiative equilibrium having a thickness of about  $4.5 \times 10^5$  km (see Figure 3). At the top of this layer of the sun, about  $0.7 r$  ( $r$  being the solar radius) from the center, conditions have become such that radiation alone cannot maintain the flow of energy. At this level, the temperature has dropped by orders of magnitude to about  $13 \times 10^4$  °K. The density has fallen to  $0.07$  gm/cm<sup>3</sup>.

Between  $0.7$  and  $1.0 r$  lies the region known as the convective zone. The convective zone contains about  $1/200$ th of the total solar mass, and temperatures and densities continue to drop. At the top of the convective zone, upon which the photosphere lies, the temperature has fallen another order of magnitude to about  $6000$  °K, and the density has fallen to a surprisingly low value of  $10^{-8}$  gm/cm<sup>3</sup>. Even though this layer contains convective instability, it is believed that heat transfer by convection is small relative to radiative heat transfer.

The optically visible portion of the sun is the photosphere. Upon the photosphere, relatively dark spots, called sunspots, are often seen. Some of these spots are many times larger than the entire earth. As an example, if a spot group could be covered by a silver dollar, the earth, in comparison, would be less than half the size of the normal pencil eraser. Sunspots will be discussed more fully in later sections. The photosphere has a thickness of about  $800$  km or  $0.0001$  radii, relatively cool temperatures of about  $5,800$  °K, and a density of about  $10^{-8}$  gm/cm<sup>3</sup>.



POLAR CORONAL  
BRUSHES

GRANULES

FACULA

SUNSPOTS

FACULA

PLAGE  
SUNSPOT

ACTIVE LOOP  
PROMINENCE

SPICULES

ACTIVE SURGE  
PROMINENCE

QUIESCENT PROM.

FILAMENT

SPICULES

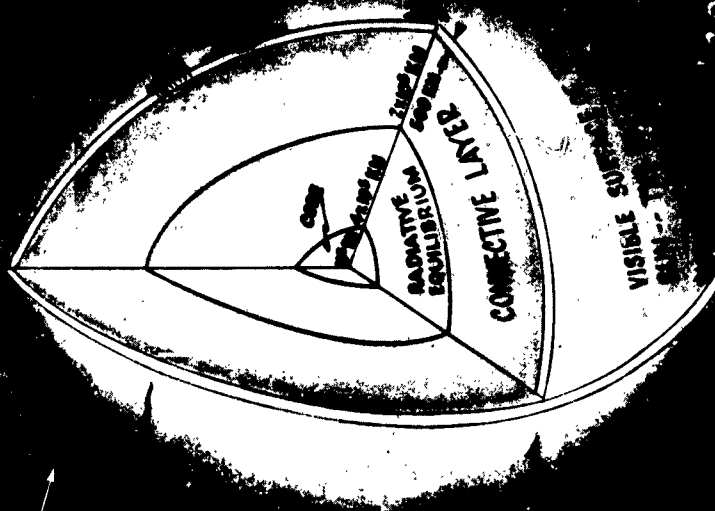


Figure 3

SCHEMATIC DIAGRAM  
OF THE SUN

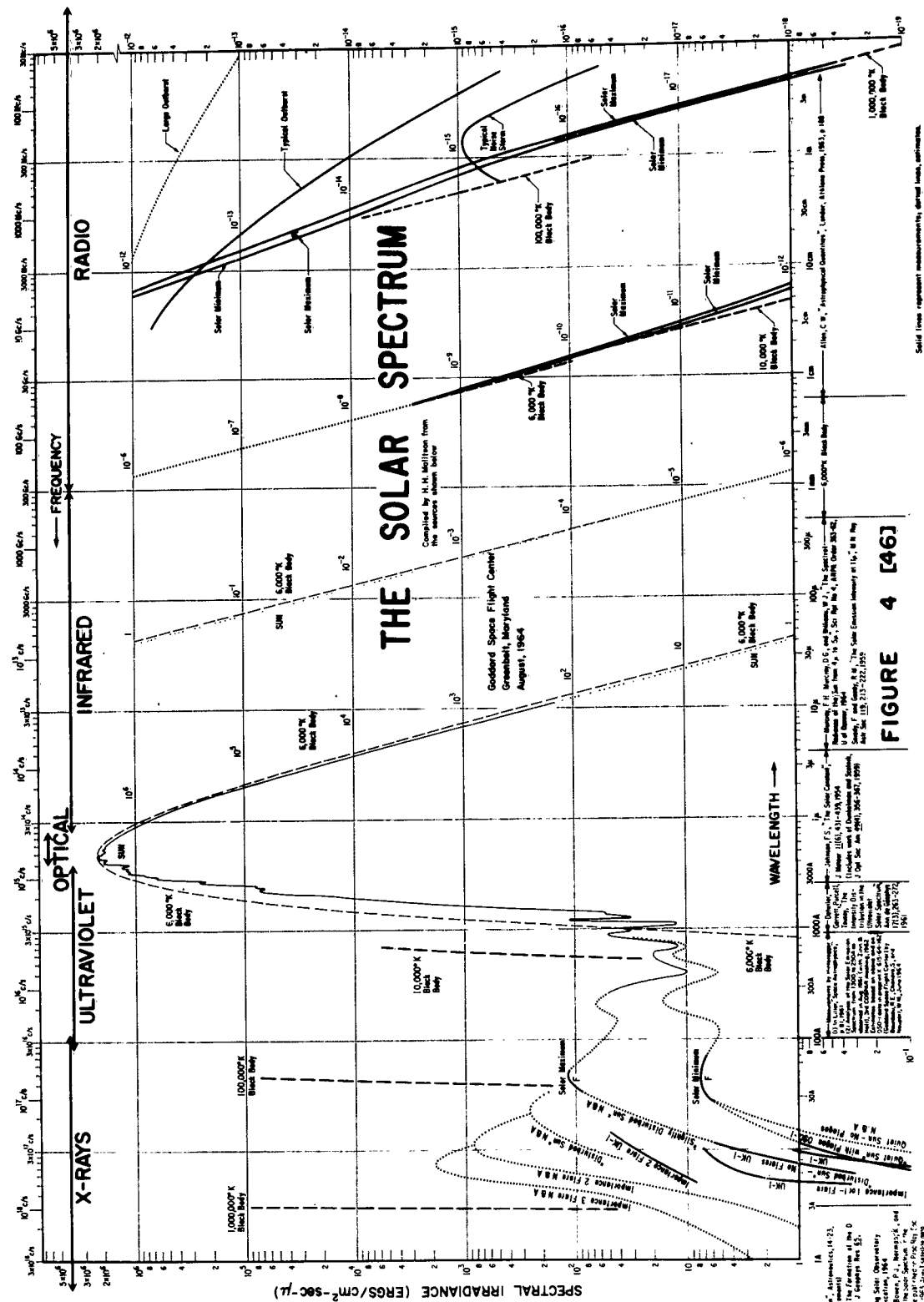
Above the photosphere lies the chromosphere. It is the solar atmospheric transition layer. It has a thickness of 3,000 to 5,000 km over most of its area, and a temperature gradient forming the transition from the relatively cool photosphere to the  $10^6$  °K or more in the layer immediately above, i.e., the corona.

The corona is composed chiefly of hydrogen gas at temperatures on the order of  $10^6$  °K near the sun. These high temperatures ionize the gases of the corona into protons and free electrons, i.e., a plasma. The temperatures are apparently caused by the dissipation of sound waves and hydromagnetic waves generated in the convective layer. The corona has been found to extend at least beyond the orbit of the earth. It is unknown just how far the corona does extend, but it is thought to extend perhaps to the belt of the asteroids. The corona's particle density is about  $3 \times 10^7$  particles per cubic centimeter near the sun and about  $10^3$  particles per cubic centimeter near the earth [66].

#### b. General Description of Energy Emission.

##### (1) Constant.

In the sun's interior, energy is produced at the rate of  $4 \times 10^{33}$  ergs/sec, mainly by the proton-proton chain of nuclear reaction in which hydrogen is converted to helium. Yet this rate of energy production per pound is only  $5 \times 10^{-3}$  that of the human body. The sun's total radiation over the entire spectrum is 7 kilowatts per square centimeter ( $\text{KW}/\text{cm}^2$ ) of its surface. All but about one percent of the emitted energy is concentrated in the narrow band 0.3 to 4.0 microns, which includes the visible range. Energy emission over almost the entire spectrum, except the two extremes, is nearly invariant (see Figure 4). The solar constant, defined as the total radiation during one minute over  $1 \text{ cm}^2$  of area normal to the sun's rays at the outer limit of the earth's atmosphere at the mean distance of the earth from the sun, is  $0.140 \text{ W}/\text{cm}^2$  (1.94 calories per square centimeter). The varying distance of the earth from the sun produces a change of  $\pm 3.5\%$ . Any other changes which may occur in this value are so small they are difficult to establish. However, a recent planetary method of measuring the sun's radiation output suggests that a 2.5% increase occurred over the period 1954-58 [61]. It must be mentioned that this increase in radiation is not considered valid by most authorities. In the planetary method, solar radiation is measured by comparison of the reflection from the surface of a planet with the background of stars of known brightness. Thus the atmospheric absorption and scatter cancel out. Previous calculations showed variations of less than 0.3% over the period 1923-1952.



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## (2) Variable: bto.

Radiation in the very short wavelengths, including ultraviolet, X-rays and gamma rays, and in the very long radio wavelengths, is extremely variable. Changes by factors of  $10^2$  to  $10^5$  occur over periods of minutes. The extreme ultraviolet (EUV, 100 to 900 A\*) has two variable components: one radiated from active (sunspot) areas, correlated with 10.7-cm solar radio flux, and the other radiated as a background emission which is rather uniformly distributed over the entire sun, and not correlated with the 10.7-cm flux. While the short wavelengths comprise less than 1% of the total solar output, they produce important effects on the interplanetary environment.

The sun radiates over the entire electromagnetic range, but only wavelengths in the narrow optical window 2,900-30,000 A and the radio window 1-cm to 40 meters (m) reach the surface of the earth. All other radiation is absorbed by the atmosphere. Wavelengths shorter than 2,900 A have never been observed at the earth, even on mountain peaks. Between 2,200 and 2,900 A, ozone is the principal absorber. Molecular oxygen absorbs wavelengths 2,200 to 900 A below the 75-km level, and all species of atmospheric constituents absorb wavelengths shorter than 900 A below the 150-km level. Some infrared is transmitted between 1 and 24 microns, and some radio waves filter through above 1 or 2 millimeters (mm). The atmosphere is transparent to wavelengths of 4-mm to 40-m, but longer wavelengths are reflected by the ionosphere [33].

The total electromagnetic radiation of the sun is equivalent to that of a black body at  $5,800^\circ\text{K}$ , and the visible and infrared portion to  $6,000^\circ\text{K}$ . Infrared emission up to about 15 microns is regular and smooth, but is completely absorbed by the atmosphere in certain bands. (See Figure 4).

The spectrum of the photosphere from 3,000 to 13,000 A is composed of a rainbow continuum characteristic of black body emission, channeled by more than 26,000 dark Fraunhofer absorption lines. The absence of light in these lines is caused by absorption in the upper levels of the solar atmosphere. Each element absorbs its own colors or wavelengths, thus providing a key to the substance of the solar atmosphere.

Most of the light of the corona is a strong, continuous spectrum with an energy distribution similar to that of the

\* A = Angstrom unit =  $10^{-8}$  cm.

photosphere. The spectrum of the inner corona, which lies within 5 to 10 minutes of arc of the limb, is a continuum which arises primarily from electron scattering. The continuous spectrum of the middle and outer corona consists of a K component which evidently arises from electron scattering, and an F component which is a pure reflection of the Fraunhofer spectrum. Emission lines appear in the middle and outer corona, and in the outermost portion, the Fraunhofer absorption lines appear. The important lines of the coronal spectrum are green (5303 Å), red (6375 and 6702 Å), infrared (7892, 10747 and 10798 Å) and ultraviolet (3388 Å). The width of these lines is 0.8 to 1.0 Å [1].

The continuum radiation of the sun at short wavelengths probably does not change perceptibly over the solar cycle. However, the line radiations, probably for wavelengths less than 1800 Å and particularly in the X-ray region below 30 Å, have a large variation approximately in phase with the sunspot cycle. Emission lines contribute only a minor portion of the radiation above 1400 Å, but a major portion below this wavelength. From 220 down to 20 Å the dense distribution of spectral lines is similar to a gray body at  $5 \times 10^5$  °K. Below 20 Å the intensity depends a great deal upon sunspot activity, with sudden changes occurring during solar flares. During flares, the shortest wavelength normally observed is 1.0 Å, although 0.15 Å (energies as high as 80 Kev+) and 0.02 Å (500 Kev) occur for rare, brief periods. [6].

There is little information on the relative variation in different lines. The Lyman- $\alpha$  resonance line of hydrogen (1215.7 Å) appears to be relatively stable although it is emitted non-uniformly over the solar disk, causing the disk to have a splotchy appearance. This property is also characteristic of other lines. The variations have little effect on the solar constant, but have important effects on ionization and density in the earth's ionosphere. Variations in gamma-ray and X-ray wavelengths over the solar cycle have not been fully determined because they can only be measured from altitudes high above the earth's surface. Solar cosmic rays which reach the earth include protons over the range from a few Mev\* to a few Bev#, alpha particles, heavy nuclei, and electrons. High energy protons travel from sun to earth at about one-half the speed of light. Solar particles are channelled into the polar regions by the earth's magnetic field, but only in rare instances is their energy so great that they reach the surface. The sum of X-ray and ultraviolet radiation amounts to at most  $10^{-3}$  of the solar constant,

+ Kev - "kilo"electron volts, i.e., Thousand Electron Volts.

\* Mev - million electron volts.

# Bev - billion electron volts; more recently renamed "GEV" or "Giga Electron Volts, which remains, however, a billion electron volts or  $10^9$  ev.

and normal corpuscular radiation to  $10^{-4}$  of the constant.

## 2. The Quiet Sun.

### a. Photosphere.

The photosphere, which is the main visible portion of the solar disk, has a granular appearance. Irregular bright areas, or granules, 300 to 1800 km across, are uniformly distributed over the surface with dark lanes between (see Plate I). After reaching maximum size they disintegrate into smaller fragments and disappear. Granules are very likely the tops of convective cells emerging through the photosphere from the convective layer.

The root-mean-square brightness fluctuation between granules and dark lanes is about 4.6 percent, or  $\pm 60^\circ$  K. over constant optical depth. The granules are likely elevated above the dark lanes, and since the temperature decreases outward, the temperature fluctuations at constant geometrical depth are probably much greater. The granular structure has no known systematic changes with time.

Both temperature and density in the photosphere decrease outward. Since the optical thickness increases toward the limb of the sun, radiation from the deeper, hotter layers is reduced, and the continuous spectrum corresponds to a lower temperature. This is the physical explanation of limb darkening, which is very visible on Plates VII and X. The amount of limb darkening is more pronounced at short wavelengths, and is different for various spectral lines. In fact, in certain lines there is limb brightening. Nearly all the elements appear in the spectrum of the photosphere. The visible portion of the spectrum radiates at a temperature equivalent to a  $6000^\circ$  K black body. In the upper photosphere, absorption of radiation reduces the effective temperature to about  $4200^\circ$  K. The particle density of the photosphere is about  $10^{16}$  per cubic centimeter, which is only about  $10^{-3}$  times the particle density of the earth's atmosphere [32].

### b. Chromosphere.

The chromosphere derives its name from the red glow visible either for a few seconds during a total solar eclipse, completely surrounding the disk of the moon, or with the Lyot coronagraph (see Section 7.c.) which artificially eclipses the photosphere of the sun. The red color is derived primarily from the red line of hydrogen (6563A). A view of the chromosphere is obscured by the brilliant

photosphere during non-eclipse conditions. During eclipses the spectacularly beautiful, widely extended corona detracts one's attention (see Plate II). The chromosphere is the chaotic boundary layer between the relatively cool, dense photosphere and the hot, tenuous corona. In general it is 3,000 to 5,000 km thick, with an active and irregular surface. The top of the layer is defined rather vaguely as the upper boundary of emission of the Balmer- $\alpha$  line of hydrogen, (hydrogen-alpha or H- $\alpha$ ) exclusive of prominences. The H (3968.5 Å) and K (3933.7 Å) lines of Ca II are also suitable for observation of the chromosphere (see Plate III). The emissions in different lines show different height levels and are the result of different physical processes.

Covering about one percent and uniformly distributed over the area of the chromosphere are fine jets of matter which are ejected upward into the corona at velocities of 25 to 30 km/sec [18]. These jets are called spicules and rise to average heights of about 7500 km at the equator and 9000 km at the poles (see Plate IV). They deviate up to  $30^\circ$  from the vertical along magnetic lines of force, and have a diameter of something less than one second of arc ( $\sim 725$  km). At the limb, spicules appear to cover a large portion of the surface, but this is only because of foreshortening due to the angle of observation. The lifetime of individual elements is 5 to 10 minutes [18]. Assuming random distribution, spicules would occur over one half the disk in 24 hours. Spicules are attributed to material ejected into the corona along magnetic lines of force by shock and magnetohydrodynamic disturbances. [17].

The chromosphere is inhomogeneous and cannot be approximated by a single layer model. Various theories propose lower chromosphere temperatures ranging from  $5000^\circ\text{K}$  to  $30,000^\circ\text{K}$ . A model by Wooley and Allen [32] is adequate for producing the flux required for the formation of the earth's ionosphere. In this model the temperature is  $6000^\circ\text{K}$  in the lowest level and increases rapidly to several hundred thousand degrees above the 6000-km level. Radiation in the upper chromosphere is produced by recombination of protons and electrons, and by the excitation of line emissions in stripped atoms of the lighter elements. In the model of Shklovsky and Kononovich [32] the chromosphere has hot regions which have temperatures of  $12,000^\circ\text{K}$ , extend to 8,000 km in height, and cover 10% of the surface. The remainder of the surface has a temperature of only  $4,000^\circ\text{K}$  and extends in height to 6,000 km. There is disagreement on the temperature values, and on whether the spicules are part of the hot or cool regions. It is clear, however, that the temperature gradient from the chromosphere to the corona is very steep.

#### c. Corona.

The corona consists of highly ionized gases, mainly hydrogen, with 10% to 20% of helium, and heavier atoms which may have lost up to 15 of their electrons [25]. Near the sun, the gas kinetic

temperature of the corona is estimated at one to two million degrees K, depending on height and method of measurement. Particle density is estimated at  $3 \times 10^7$  protons and an equal number of electrons per cubic centimeter, decreasing exponentially to  $10^3$  particles per cubic centimeter at the earth's orbit.

Due to a remarkable coincidence, both the sun and moon subtend angles of almost one-half of a degree of arc as viewed from the earth. Thus at total eclipse the moon almost exactly covers the disk of the sun, and the corona becomes visible as a faint white halo with a slightly greenish cast spreading millions of kilometers into space (see Plates II and V). Scattering and focusing of meter radio radiation from the Crab nebula by the outer corona show that the corona extends out to at least 20 solar radii[61]. At 40 solar radii the light from the corona merges with that of the Zodiacal light\* making further observation difficult[1]. Thus there is no known outer boundary of the corona. With a coronagraph, it is possible to photograph the corona routinely out to 0.3 to 0.5 solar radii.

The visible portion of the coronal spectrum is divided into three components. The K (electron) component is a white continuum produced by Thompson scattering of light from the photosphere by free electrons. It is partially polarized and contains no Fraunhofer lines. Observations during eclipses show a highly irregular, non-symmetric structure about the sun. (Line observations of the F component show even more irregular detail). The F (dust) component, which is the halo produced by interplanetary dust particles, is also a white light continuum, but is unpolarized and contains the Fraunhofer lines. The dust corona may be the source of the Zodiacal light. The L (or E, emission line) component consists of 31 emission lines between 3328 and 10,728 Å. The most important of these lines are: green (5303 Å), red (6375 and 6702 Å), infrared (7892, 10747 and 10798 Å) and ultraviolet (3388 Å), all of which have line widths about 0.8 to 1.0 Å as mentioned before. The kinetic temperature of the corona is about  $10^6$  °K. In some regions, however, excitation states of ions and line profiles indicate temperatures of the order of  $3-5 \times 10^6$  °K. These extremely high temperatures are required to satisfy the following features: (1) the great extent of the corona, (2) the absence of Fraunhofer lines, (3) emission lines originating in highly ionized heavy atoms, (4) Doppler broadening

\*Zodiacal light - A faint wide streak of light seen about an hour after sunset in the plane of the ecliptic. It is light from the sun scattered by dust and ionized gas. The plane of the ecliptic is the plane in which the earth revolves around the sun.



of coronal lines above 1 A, (5) absence of low-temperature spectral lines, and (6) the characteristics of the radio spectrum[32]. The high temperatures can be explained by the dissipation of shock-wave energy[33].

Cor.

Soundwaves generated by turbulence start within the hydrogen convection zone below the photosphere and propagate outward, increasing in amplitude as the density decreases, until supersonic pressure waves develop. Only a small amount of the shock-wave energy needs to be dissipated in the corona to achieve very high temperatures. The temperature is maintained because hydrogen is about  $10^4$  times more abundant than gaseous state metals, and hydrogen loses heat by radiation much less effectively than do metals. For instance, a star composed mainly of iron would have a much cooler corona.

The brightness of the corona is about  $10^{-6}$  of the brightness of the center disk and falls off approximately as the 6th power of distance from the limb. The total light of the corona varies with the sunspot cycle, and is about doubled at solar maximum.

Both the geometry and the line emission of the corona vary over the sunspot cycle. At sunspot maximum the outer corona is nearly spherical (see Plate V), whereas the inner corona appears highly irregular. Line emission is at its highest average level, both as a result of higher density and higher temperature. At sunspot minimum, the outer corona becomes distorted, with equatorial streamers extending to several solar diameters, and shorter streamers at the poles, suggesting magnetic lines of force.(see Plate II). Coronal line emission, electron density and temperature are at their lowest average values during sunspot minimum.

### 3. The Disturbed Sun.

#### a. General.

The highly variable portion of solar activity is concentrated in local migratory active areas, which are the origin of certain types of prominences, flares, and corpuscular and electromagnetic radiation. A center of activity (CA) is defined as the sum of all optical and radio-frequency manifestations associated with a magnetic region which may at some time contain a spot. The last optical evidence of a CA is a quiescent prominence which may persist for several months. The "importance" of a CA is defined by duration, intensity, and extent of plages, and the number and dimensions of sunspots it contains. There is a scale of increasing importance from 1 to 10. In general, solar activity follows an average cycle of about 11.2 years over which it ranges from very little activity to a high level. The observed period between solar minima has varied from 8.5 to 14 years, and the period between maxima from 7 to 17 years. There is a variation

of intensity of activity by a factor of two or more between the peaks, and random short period cycles are superimposed on the long period trend. During years of high activity there are numerous CA's scattered over the solar disk in various stages of development. Centers of activity form systematically nearer and nearer the equator during a cycle implying large, streaming currents beneath the photosphere which may be related to the non-uniform rotation of the sun. Following a solar minimum, CA's tend to re-form near  $40-45^\circ$  latitude north and south. Toward the end of the solar cycle, activity is concentrated near the equator at about  $5^\circ$  north and south latitude. By this time new centers may have formed near  $40-45^\circ$ . Individual centers of activity show the equatorward trend, but have much shorter lifetimes. Either the northern or southern solar hemisphere may contain the larger number of active centers, but in recent cycles a much larger proportion of severe activity has been produced in the northern hemisphere.

The 11-year cycle is thought to be superimposed on a periodicity of about 90 to 100 years [13] which seems to rise slowly to a maximum and then fall off rapidly, in a sawtooth pattern (see Figure 5). The 1958 solar maximum seems to be at the tip of one of the sawteeth from which one might predict that the next maximum may be lower. There is also some indication of a 30-year periodicity.

#### b. Disturbances of the Photosphere

##### (1) Sunspots

Sunspots are the oldest form of solar disturbance known to man. They appear as dark splotches against the disk because their temperature is lower than that of the surrounding photosphere by as much as  $2,000^\circ$  K. The temperature difference provides enough contrast so that near sunrise or sunset the larger spots may sometimes be distinguished with the naked eye. However, looking at the sun with the naked eye is not recommended. The temperature difference may be produced by a strong local magnetic field which impedes the transfer of heat to the surface by thermal convection. Because of the lower temperature the solar atmosphere above a sunspot becomes less opaque and we see farther down into it. Thus, a sunspot probably represents a depression in the photosphere, and since the temperature of this layer increases inward, the actual temperature difference between a sunspot and its surroundings at the same level is probably larger than the apparent value.

Sunspots have a dark center, or umbra, surrounded by a ring of brighter radial filaments, the penumbra. The umbra may reach

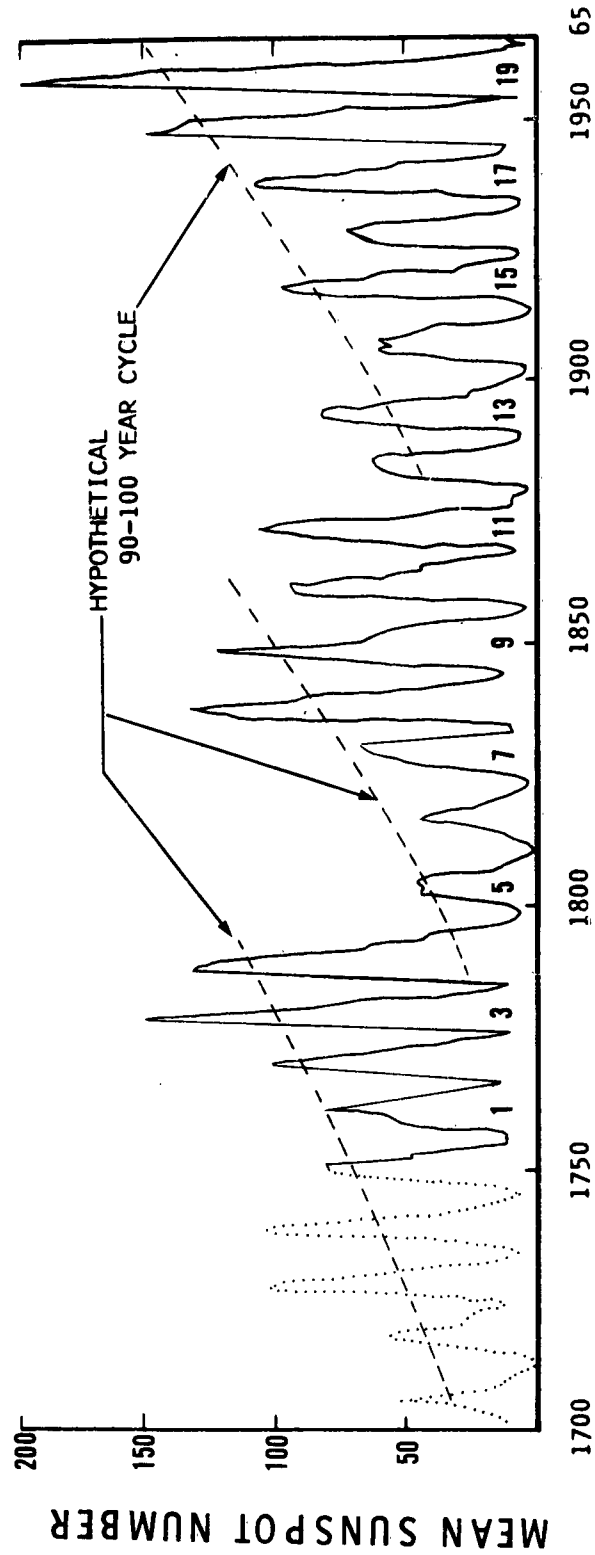


FIGURE 5. VARIATION IN MEAN SUNSPOT NUMBERS. (ZURICH DAILY RELATIVE VALUES; ADAPTED FROM REF. [25])

a size of 75,000 km across and the entire spot up to 100,000 km. Spots vary greatly in size, but the proportion of large to small spots is nearly constant over the solar cycle. Individual elements of the penumbra have dimensions of about 300 X 500 km, and may be individual convective cells. Both umbra and penumbra have a granular appearance (see Plate VI); elements of the former have a lifetime of about two hours and of the latter, several hours. The umbra has been found [1] to range in temperature from 3920° to 5610° K (0.03 to 0.85 of the brightness intensity of the photosphere) and the penumbra from 5210° to 5580° K (0.52 to 0.82 of the brightness intensity of the photosphere). In the vicinity of a spot, material circulates inward toward the center in the upper layers, and outward in the lower layers. (This circulation is called the Evershed effect). Penumbra area is used as one predictor of solar activity, but is liable to errors such as foreshortening near the limb. Observations on the lifetimes of sunspots are variable because of the difficulty of classifying small, transitory spots or "pores". The average lifetime has been variously estimated at less than a day to six days, but it seems agreed that the maximum is about eight months.

Sunspots appear mainly in pairs or groups, the groups usually containing a few spots but occasionally several dozen. A typical prominent group will appear as small spots formed in the pores between granules. Two main spots develop and separate to a distance of 10° or more. The smaller, following spot reaches a maximum size in three or four days; the larger, leading spot in seven to nine days. Smaller spots may develop in the group. The following spot breaks up and disappears in a few days or weeks, while the leading spot decays more gradually over a period of weeks or months. Groups may persist for several solar rotations, but sometimes change significantly from one day to the next, particularly in the early stages. Sunspot area (A) is measured in units of millionths of the area of the visible solar disk.

Sunspot groups are classified according to the table below:

Table 1. Mt. Wilson Classification of  
Sunspot Groups [69]

$\alpha$	unipolar
$\beta$	bipolar
$\beta\gamma$	semicomplex
$\gamma$	complex
p	in preceding part of plage
f	in following part of plage

Table 1 continued:

Magnetic Classification:

- a weak field, usually bipolar
- b. single polarity with strong fields; complex polarity with weak transient fields
- c strong fields of both polarities; usually found only in  $\beta\gamma$  or  $\gamma$  spot groups

The undisturbed solar magnetic field has a field strength of perhaps one gauss. However, the active regions marked by sunspots have strong local fields of up to 4000 gauss. The magnetic field of a spot reaches a typical maximum of around 3000 gauss and remains fairly constant in the overall sense for about 30 days [1]. Thereafter, it declines slowly at first, and then more rapidly. Superimposed on the long-term trend are short-period variations of 20 or 30 gauss per hour. Most spot groups are bipolar, with a dominant spot in the western (leading) edge of the group having opposite polarity from the rest. However, some spot groups have single or multiple polarity. The polarities of groups in one hemisphere tend to be alike during any one solar cycle, but opposite to the other hemisphere; however, there are many exceptions. In recent records the polarity has reversed between hemispheres from one solar cycle to the next.

Sunspot number, or Wolff number,  $R$ , is the most commonly used index of solar activity, is the one for which the longest records are available, and is the basis for establishing the solar cycle.

$$R = K(10g + s)$$

where  $K$  is a constant of proportionality which varies for each observer and observatory (usually equals about one or less),  $g$  is the number of groups, and  $s$  is the number of individual spots. The Wolff number unfortunately gives no information on size or magnetic properties and gives too much weight to small groups, besides varying with observers, observing sites, and observing conditions. One may reflect on the difficulties this situation alone imposes on the problem of solar prediction. Empirical corrections are applied to  $R$  in order to compare data from various observatories. The yearly average of  $R$  varies from 46 to 190 during solar maximum and 0 to 11 during solar minimum [56]. During the quiet portion of the cycle, periods of several weeks may pass in which no spots appear at all.

Sunspots mark the location of all important active centers, but they are only the visible, and not the primary, physical phenomenon of an active region.

## (2) Faculae.

Faculae are patchy, vein-like bright regions found in the upper portion of the photosphere. They surround all sunspot groups and are most pronounced around the periphery of large, active groups, but they also occur separately at high latitudes. They are normally visible only within  $40^\circ$  or less of the limb of the sun (see Plate VII). Their brightness requires that they have a higher temperature than their surroundings. Faculae have an average duration three times that of the associated sunspots, appearing earlier and persisting longer. They are made up of granules about the same size as photospheric granules, with lifetimes of about two hours. These structures have a temperature about  $900^\circ \text{K}$  hotter than their surroundings, and brightness contrast 10% to 40% above the background [1].

## c. Disturbances of the chromosphere.

### (1) Plages

Above the photospheric faculae are the bright plages (or chromospheric faculae) which may be observed in the light of calcium or hydrogen- $\alpha$ . These are known to originate in the chromosphere because they appear in the spectral lines which are formed there. Plages resemble faculae in distribution, association with sunspots, and duration, but are much larger, and are visible over the entire solar disk (see Plate III). Large plages have an area of  $6 \times 10^{10} \text{ km}^2$ . They are easily observed and followed, and are closely associated with other solar phenomena which have important terrestrial influences. Little is known of the physical conditions which produce them. Calcium plages cover a maximum area of the solar disk at the peak of the 11-year cycle, and may disappear at solar minimum. About 80% of the intensity of Lyman- $\alpha$  photographs comes from the plage and only about 20% from the background. From this, it is assumed that the solar cycle variation of Lyman- $\alpha$  radiation ought to be about five to one.

### (2) Moustaches.

Moustaches are small bright points which produce broadband ( $\sim 10 \text{ \AA}$ ) brightening on either side of the H- $\alpha$  line; they apparently originate below the corresponding center of H- $\alpha$  [61]. Lifetimes are about 10 minutes. They often occur in the vicinity of spots, and rarely in plages with no spots. They are termed solar bombs by Ellerman and petits points by Lyot (see Plate VIII).

### (3) Prominences and filaments.

#### (a) General.

Prominences consist of bright clouds of hydrogen moving either upward or downward in the solar atmosphere and may be condensations of the corona produced by local magnetic fields. They appear as red luminescent shapes at the limb of the sun and are easily visible at total eclipse (see Plate II). They can now be most easily viewed with a coronascope (see Section 7.c and Plate IX). With a spectrohelioscope or Lyot filter they are observed against the bright disk as dark, irregular filaments which are the projection, as viewed from above, of relatively stable prominences lying across the lines of force at the top of an arch connecting two magnetic regions of opposite polarity. They appear dark because they absorb more (monochromatic) light than they emit along the line of sight. Typical prominences reach heights of 100,000 km and extend 150,000 km horizontally, but are only about 5,000 km thick [337]. A prominence may develop over a period of several months, then go through an explosive phase and erupt into space with a velocity as high as 700 km/sec, leaving no trace (see Plate X). Within a few days, a new prominence may form in the same location. The spectrum of a prominence is a faint continuum with bright emission lines, similar to that of the chromosphere. Most prominences are composed of a fine structure of radial filaments (see Plate XI). Irregular patterns of knots or condensations closely following each other move outward along each filament. Individual knots are specks at this range but they are comparable in size to the earth or moon (see Plate XII). They are usually elongated parallel to the direction of movement (they appear like and are named "sausages") but sometimes lie across it ("fishbones").

Prominences have many forms, and are classified in various ways according to their appearance and activity. Much of the terminology is commonplace, giving evidence that the physical understanding of these phenomena is at an early stage. One of the important means of classification is by "Active" and "Quiescent".

#### (b) Active vs Quiescent.

Active prominences are associated with areas of solar disturbance or centers of activity, have rapid motions and changes in brightness, and last no more than a few hours. They extend above the chromosphere as much as 50,000 km, and move at speeds varying from 50 to more than 1,000 km/sec. Prominences are cool relative to the surrounding hot corona into which they are projected, but have electron densities 1,000 times greater than the surrounding corona. In prominences associated with sunspots, such as

loops (see Plate XIII) and surges (see Plate XIV), temperature measurements have ranged from 7,000 to 50,000 °K and above--much hotter than in quiescent prominences, which show kinetic temperatures of about 10,000°K, about the same as the chromosphere at 1500 km height. However, it is likely that the most reliable values are near 15,000° K [1]. The spectra divide sharply between the two types, suggesting two distinct, thermally stable temperature levels. Quiescent prominences consist mainly of emissions of calcium, hydrogen and helium, while the active types show numerous spectral lines of other metals. Quiescent prominences are not immediately associated with centers of activity but form on the poleward side of them, then drift poleward. Their density is greater than that of surrounding coronal gases, and they are apparently supported by the strong magnetic fields of nearby active regions. Even quiescent prominences show a great deal of turbulent internal motion with velocities of 5-10 km/sec. Occasionally, quiescent prominences which have been present for some time become active and erupt outward in sudden disappearances (see Plate X) which are probably due to unstable, explosive disturbances of the supporting field [19]. A new quiescent prominence of the same form commonly recurs within a few hours. There are also abrupt disappearances associated with flares and lasting only a minute or so, probably caused by bombardment by high speed flare particles.

(c) Menzel/Evans/Jones

The table below gives the Menzel/Evans/Jones method of classifying prominences according to direction of flow, association with sunspots, and shape.

Table 2. Menzel/Evans/Jones Classification of Prominences [49]

A - Prominences originating from above, in the corona

S - Sunspot Prominences

- a. rain [50]
- f. funnels
- l. loops

N - Non-Spot Prominences

- a. coronal rain
- b. tree trunks
- c. trees
- d. hedgerows
- e. suspended clouds
- m. mounds



B - Prominences originating from below, in the chromosphere

S - Sunspot Prominences

N - Non-spot Prominences

s. surges

s. spicules

p. puffs

Type A prominences have an unexplained origin in the corona, and have elements moving downward toward the photosphere. Type B prominences originate in the chromosphere and move upward into the corona. Classes AS and BS are active. AN and BN are quiescent types as described above. Interactive prominences are those which are connected by streamers in which material moves in both directions. About 90 percent of prominences are of the A type, in which closely following knots describe a downward trajectory along the lines of force. Occasionally a rotary or spiraling motion occurs. Ascending hedgerows sometimes show rotation in a horizontal or vertical plane. In many hedgerow prominences (depicted in Plate XI) there is a rapid acceleration of downward flow, followed by a reverse in direction to form an upward expanding arch, giving the appearance of changing from class A to B. Matter continually filters through an A prominence, appearing from an unknown source at the top and disappearing at the bottom. Plate XIII depicts loops and arches (AS1) in which material flows downward along both sides of the arch. The speed of descent usually ranges from 10 to 20 km/sec, so that the substance of a prominence 150,000 km high changes about every three hours. The continuity in shape is apparently maintained by strong local magnetic fields. Loops (AS1) and rain (ASa), which form over sunspots, undergo rapid changes in shape coincident with changes in the magnetic fields of the sunspots[50].

Menzel has proposed a model to explain the field anomaly which supports a type A prominence. Normally, the magnetic field of the corona has lines of force parallel to the surface of the sun. Suppose that a disturbance causes an area of the corona to cool rapidly by ultraviolet radiation. The cooled gas subsides, carrying lines of force with it. If the displacement exceeds the width of the disturbance, second-order forces come into play which cause bubbles of ionized gas to break through the lines of force. A vertical column of such bubbles would be adequate to support observed prominence forms. Magnetic fields of around 150 gauss have been measured in active prominences, and fields of about 50 gauss in quiescent ones [50].

Types (AN) consist of filamentary curtains extending 50,000 to 150,000 km in height, 80,000 to 700,000 km in length and 5,000 km in width. Those which resemble trees (ANc), tree trunks (ANb) and mounds (ANm), may be hedgerows (AND, see Plate XI) lying parallel to the line of sight. These often change in appearance when a new sunspot group develops. Hedgerows often gradually ascend if they are near a sunspot group. Coronal rain (ANa) consists of streamers originating high in the corona, and may persist several days. In loops (ASl) and rain (ASa), matter descends at 100 to 200 km/sec, 10 times the descent rate of other A types. Loops appear suddenly as a brilliant knot from which material flows downward along two paths.

Class B prominences originate in the chromosphere, whose structure is largely composed of the spicules (BNs) described earlier. A surge (BSs, see Plate XIV) consists of filaments rising upward with an approximately uniform velocity of 300 to 600 km/sec, although in extreme cases velocity reaches 1,000 km/sec. Surges protrude from the originating sunspot at all angles. A typical ascent lasts about 15 minutes, after which the material fades or falls back into the chromosphere along the line of ascent within about an hour. Surges are closely related to flares. A puff (BSp) is a separate knot of luminous material which is ejected at surge velocity, then fades away or falls back along the line of ascent [50].

The size of prominences is measured in the international prominence unit N, which is a rectangle one heliocentric degree long and one geocentric degree high [49]. Importance is graduated from a maximum of A+ to a minimum of D-.

(d) Pettit.

An outline of Pettit's classification is shown below. This classification and the Menzel/Evans/Jones classification are the most widely used of various classification schemes. It seems probable, however, that the latter classification provides a better description of prominences since it describes something of the origin of the various types of prominences.

Table 3. Pettit's Classification of Prominences.

1. Active

Most frequent; filaments wave on a curved path.

2. Eruptive

Usually occur in sunspot zones; material moves toward a center and rises.

## 3. Sunspot

Wisps appear above a sunspot, brighten, and descend.

## 4. Tornado

Rare, tornado-like appearance.

## 5. Quiescent

Little general motion; drift poleward; average duration four solar rotations.

## 6. Coronal

Long strips at great height, descending at 100-200 km/sec into regions of attraction.

## (4) Flares

## (a) General.

Flares are sudden, transient brightenings in the chromosphere of portions of a previously existing plage; they are the most spectacular active phenomena of the sun. Even so, they can rarely be seen in white light. Ordinarily they can be observed only in monochromatic light with the aid of a Lyot birefringent filter or spectrohelioscope\*. They produce strong Fraunhofer absorption lines in the visible range such as the Balmer lines of hydrogen and lines of ionized calcium, and emission lines of He I, (neutral helium), Fe II (singly ionized iron), and other metallic elements. In H- $\alpha$  light (6562.85 Å) the flare region increases in brightness 4 to 15 times. The central intensity of the H- $\alpha$  line may exceed that of the adjacent continuum so that the normal absorption line becomes an emission line. In the strong helium lines either absorption or emission may be produced.

## (b) Location.

Flares originate in the chromosphere and normally do not extend much above it, although a few extend some distance into the lower corona. They occur suddenly and have a brief

\*A Spectrohelioscope images the sun in a spectral line, such as the red H- $\alpha$  line of hydrogen or the violet K line of calcium. (see Section 7.b(2))

duration, typically reaching maximum brightness in less than five minutes and decaying within 20 minutes to an hour. They are events of cataclysmic proportions, the energy output of a single large flare being equal to the entire normal output of the chromosphere and corona, or the explosion of a billion H bombs [19, 66]! The total energy of a single flare has been estimated at  $10^{32}$  -  $10^{35}$  ergs, of which  $10^{30}$  ergs are emitted in the form of high energy solar particles. Energy of this magnitude accelerates some protons and electrons up to one half the speed of light or more, and ionized gases (plasmas) up to 1100 km/sec. There are great difficulties in the interpretation of flare spectra due to departures from thermodynamic equilibrium and uncertainties concerning size, shape, and height, except for flares which appear at the limb.

All flares occur in the plage regions associated with sunspots, and rarely are seen more than  $10^5$  km from a sunspot [32]. They follow the major or minor dark filaments associated with CA's and may coincide with the disruption or fading of distant dark filaments. Flares sometimes develop in the same areas as loop prominences and surges, which have become excellent indicators of potential flares, and some occur in areas where spots have disappeared. They occur most frequently in magnetically complex spot groups of types  $\beta\gamma$  and  $\gamma$ . CA's vary greatly in the number of flares produced. Flare activity is greater during solar maximum, and nearly absent during solar minimum. Small flares appear as simple bright circular patches, while larger flares have irregular patterns of bright filaments  $10^4$  to  $10^5$  km across (see Plate XV).

#### (c) Classification.

Flares are classified according to the area covered as Importance (Imp) 1, 2, or 3 in order of increasing size, with + or - appended as appropriate. Table 4 gives an objective comparison of flare Importance.

Their frequencies during active periods range from one every half-hour or so for Imp 1 to a few times a year for Imp 3+. Flares of Importance 1, 2, and 3 occur with a relative frequency of 0.72: 0.25: 0.03. About 20,000 subflares, and 6,000 flares of Importance 1, 2, or 3 were reported during the IGY [1]. Only 4,828 flares of measured Importance were seen during the entire period 1945 through 1954, when the sun was not being observed so intensively. The size of observed flares ranges from the limit of resolution to  $3/1000$  of the solar disk, or 4,000 km in their longest dimension. Another index of flare size is the line width (The difference in wavelength between the upper and lower limits of an absorption line) or central intensity of H- $\alpha$ . Line width may increase from 2 to 20 Å, and central intensity may increase to twice the brightness of the adjoining continuum (see Table 4). Flares

Table 4. Flare Characteristics [1, 32]

Importance	Duration (minutes) Ave	Duration (minutes) Range	Area limits (10-6 visible disk)	Central Maximum In- tensity of H- $\alpha$ (%) age of adjoining continuum)	line width ( $\Delta\lambda$ ) at maximum intensity ( $\text{\AA}$ =Angstrom Unit)
1-	-	-	0-100	-	1.5 A
1	20	4-43	100-250	0.88	3.0 A
2	30	10-90	250-600	1.17	4.5 A
3	60	20-155	600-1200	1.28	8 A
3+	180	50-430	$\geq$ 1200	-	15 A

have the following geometrical characteristics[32]:

(1) They are generally irregular structures extended parallel to the solar surface.

(2) Their thickness is 3 to 4 times that of the chromosphere.

(3) They are nearly stationary as compared with prominences; their vertical growth rarely exceeding 10 km/sec.

Density within a flare is high relative to its surroundings, and temperature may be intermediate between that of the chromosphere and corona.

(d) Cause.

Flares may be caused by the sudden disruption of the intense magnetic field associated with a sunspot group, often releasing energy in excess of 500 ergs/cm<sup>3</sup>. The annihilation of a magnetic field of 1,000 gauss can supply this energy, and field strengths up to 3,000 gauss are observed in sunspots. The magnetic field strength in the chromosphere is comparable to that in the photosphere within the sunspot itself, but the density in the chromosphere is several orders of magnitude lower. Any electrical currents which flow in the gases of the chromosphere must flow along the lines of force, which may lead to hydromagnetic instability. Any perturbation would not be damped by the gas because of its low density, and the dynamical progress of instability in the plasma would be explosive[66]. Since magnetic fields are observed at flare sites after the flare has ceased, it is apparent that only a portion of the field is destroyed to provide energy for the flare.

(e) Radiation.

Flares are the source of most of the variable radiation which has important effects on terrestrial and interplanetary environment. It includes both corpuscular and electromagnetic radiation, and ranges over the spectrum from the extremely short gamma rays to radio wavelengths in the meter range. The corpuscular or particle emission from a flare consists of a stream of very high energy particles, and a huge cloud of plasma, or highly ionized gas composed of lower energy particles. The energetic particles are about 85% protons (hydrogen nuclei), 14% alpha particles (helium nuclei), and 1% heavier nuclei[17]. Of these, the protons appear most important because the alpha particles and heavy nuclei have little penetration power due to their lower energy content and larger collision cross sections.

The protons have energies of hundreds of Mev, and sometimes into the Bev range. The number of protons which reach the earth varies greatly, even between flares of the same size, and the time of arrival varies from a few minutes to several hours after the onset of the flare. The stream of high-energy protons follows the lines of force of the sun's distorted magnetic field, the transit time depending on the configuration of the field and the energy of the particles. In general, the transit of the higher energy particles is most rapid when the flare is located near the west limb of the sun, and slowest when the originating flare is near the east limb. With the lower energy protons, there seems to be a longer delay than can be explained without invoking some sort of storage mechanism between the earth and the sun. Thus it is thought that these low energy protons do not follow the magnetic lines of force. One of the unexplained facts about these lower energy protons is that their delay times are greater during solar maxima than during solar minima..

Only about 10% of flares larger than those of Importance 2 produce a sharp increase in cosmic radiation in the vicinity of the earth. Either larger numbers of higher energy particles are emitted by these larger flares, or the particles cannot reach the earth in larger concentrations unless the magnetic configuration is suitable. A total of 25 "cosmic ray flares" occurred over a two-year period during the last solar maximum. Only in infrequent, severe cases do large numbers of energetic particles, following the magnetic lines of force, reach the surface of the earth, within the polar regions. Such events come on the average only about once in two years. The correlation of these events with the sunspot cycle is not apparent, except that they rarely occur during solar minimum. For instance, during the 1952-55 solar minimum, only one cosmic ray flare occurred.

#### (f) Effects.

The lower energy protons emitted from a flare reach the earth 24 hours or more after the onset of the flare, causing geomagnetic storms, auroras, and a decrease in galactic cosmic rays (Forbush decrease).

The flux of gamma rays, X-rays, and ultraviolet rays is greatly increased by flares, with bursts which reach energy levels of 1000Mev in the early stages of large flares. The spectral distribution of X-ray flux in these cases would require thermal sources with local temperatures up to  $10^8$  °K [8]. Total X-ray flux during one Imp 2+ flare was twice the quiet sun value, in spite of the fact that the flare covered only  $10^{-4}$  of the solar disk. Enhancement of total gamma and ultraviolet emission from flares has not been reliably measured

because of the small flare area. Enhanced X-ray and ultraviolet (UV) radiation increases the ionization in the ionospheric layers on the sunlit side of the earth, giving rise to sudden ionospheric disturbances (SIDs), among which are sudden phase anomalies (SPAs), sudden enhancements of atmospherics (SEAs), and short wave fades (SWFs). The X-ray and UV radiation also cause slight but sharp perturbations of the earth's magnetic field (crochets). These effects continue as long as the flare is visible.

Larger flares are nearly always accompanied by an increase in radio noise. This noise frequently occurs in the form of radio bursts whose intensities may be several thousands of times the radio intensity of the quiet sun. Bursts originating in the chromosphere occur in the millimeter to centimeter range, while those originating in the corona are of meter to decameter wavelengths. All flares that cover significant portions of the umbra of a sunspot produce radio bursts in the centimeter range. About 2/3 of cosmic ray flares have strong centimeter radiation, and are strongly correlated with flares which have covered significant portions of umbrae of sunspots [45].

Non-cosmic ray flares which produce centimeter bursts are about uniformly distributed over the sun, but flares which produce cosmic ray events at the earth are concentrated toward the center of the disk. In cosmic ray flares, the radio emission maximum occurs later than the optical maximum, but for ordinary flares the order is reversed. Of 888 plage regions recorded during the IGY, 566 produced flares and 322 did not. Each of the five regions having the largest number of flares also had a cosmic ray event, but events also occurred in regions with fewer flares [45]. Characteristics of cosmic ray events pertaining to prediction of the events will be discussed in a later section of this pamphlet.

#### d. Disturbances of the Corona.

Coronal condensations or hot spots (see Plate XVI) which occur above centers of activity (CA's) show excessive brightening of the coronal yellow line of CA XV (the calcium atom with 14 electrons removed from the outer shells) at a wavelength ( $\lambda$ ) of 5694 Å and sometimes have a prominence-type structure [32]. The yellow line emission may be a useful indicator of the impending rise of a CA over the east limb. The condensations also show a brightening of the continuous spectrum of photospheric light, which may be attributed to an increase in electron density. Both line and continuum emissions increase by factors up to 100 with temperature reaching an estimated range from  $4.2 \times 10^6$  to  $10^7$  °K. Density



increases by a factor of 10 to 20. The diameters of the disturbances are commonly in excess of  $10^5$  km [19].

One effect of the large increase in temperature of the coronal gas is to increase the ionization of the various elements. The ionization potential increases, and the corresponding X-ray wavelength decreases (X-ray hardening) to a probable limit of thermally-excited emission at  $\lambda = 1.6$  Å for  $10^7$ °K, as the heavy ion atoms lose all their electrons. Another effect of the increased temperature is to produce violent expansions of the coronal gases which assume an appearance similar to that of chromospheric prominences.

The intensity and hardness of coronal X-ray emission show a strong relationship with the solar cycle. Near the 1953-4 solar minimum, rocket measurements indicated a marked reduction in X-ray emission below 20 Å, and in some experiments no emission was detected below 10 Å. As the solar cycle approached maximum in 1957-8, the overall X-ray flux increased, but especially at the shorter wavelengths. From 2-8 Å the total variation was a factor of several hundred; from 8-20 Å it was a factor of 45, and from 44-60 Å a factor of 7. The 44-60 Å radiation indicated that the corona had a temperature of only  $6 \times 10^5$ °K at solar minimum but increased to  $2 \times 10^6$ °K in some regions at solar maximum. An exception occurred in 1962 when the X-ray spectrum from a coronal hot spot showed greatly enhanced radiation at the shorter wavelengths, indicating local temperatures of 4 to  $6 \times 10^6$ °K.

Loops (Plate XVII) and straight or curved rays (Plate XVIII) are common among the varied configurations of coronal hot spots. There are apparent outward motions, and vertical or horizontal oscillations. Low arches in the corona above active regions sometimes disrupt violently and are designated as whips. Flashing loops appear as the illumination of curved loops at successively greater heights [61]. Above some CA's, closed loops, arches, fans, and divergent open filaments similar to prominences are observed. That some of the coronal motions are real, is shown by Doppler shifts in the spectrum, but others are probably changes in appearance due to changing thermodynamic conditions or waves of excitation.

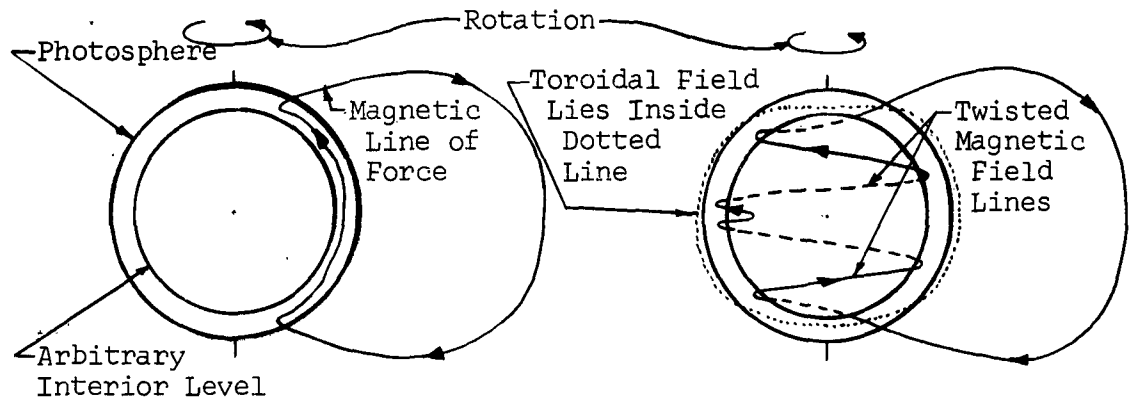
At sunspot minimum there is an extension of the corona in the equatorial direction, and short spikes appear at the poles (Plate II). At sunspot maximum the polar spikes disappear and the corona has a more uniform appearance as depicted in Plate V.

#### 4. Solar Magnetic Field.

## a. On the Disk.

Magnetic fields of the sun apparently control prominences, flare formation and other solar processes. They are also responsible for the guidance, acceleration and general control of solar particle emission, including cosmic rays.

From the shape of coronal plumes at the poles, it appears that the general magnetic field of the sun is that of a simple dipole lying along the axis of rotation and about  $2/3$  of its length. At middle latitudes the general dipole field merges into a toroidal pattern\*. In Babcock's model of the solar field, the toroidal field is produced by the non-uniform rotation of the sun. Initially, the submerged lines of force of the dipolar field lie in meridional planes in the shallow upper layers of the sun (see Figure 6a). Non-uniform rotation pulls the lines of force out in longitude to form a toroidal field (see Figure 6b). The magnetic energy of this field is increased at the expense of rotational kinetic energy. The toroidal field winds up until its intensity reaches the point of instability and it is buoyed to the surface. As this region expands into



a. Initially, a dipolar field over the entire sun.

b. After many rotations, both a dipolar and a toroidal field.

Figure 6. Illustration of Babcock's model of the solar magnetic field.

\*Toroidal field - Circular, with lines of force spiraling about the circle as in a circular coil.

the atmosphere, loops of magnetic flux are detached and may drift away from the sun carrying charged particles[1] .

General field strength in the photosphere is only about one gauss at the poles, while the field of photospheric granules may be about five gauss. Aside from the general structure, the configuration is complex and varies with time. Large areas of the disk are unipolar, others bipolar, and a few multipolar. Complexity is enhanced near the equator, although occasionally large unipolar fields appear at low latitude. In recent years polarity of the general field and of CA's in the northern and southern hemisphere has reversed during the maximum of the solar cycle[19]. H. D. Babcock reported in Volume 130 of the Astrophysical Journal (1959) that during March and July 1957, the south polar field reversed its polarity but the north polar field didn't change until November 1958. Thus for more than a year, the sun had two magnetic poles of the same sign. This curious fact is one of many that have not been adequately explained.

CA's in the photosphere have highly concentrated magnetic fields with longitudinal components ranging from a few tens to more than 3,000 gauss. The field of a sunspot remains roughly constant for about 30 days and then begins to decline, slowly at first, then more rapidly. Lesser field anomalies, which may be unipolar, bipolar or multipolar, occur over large areas which have no visual signs of activity. Plages have typical bipolar fields of about 40 gauss.

Regions which produce flares have strong magnetic gradients ranging from about 0.1 to 0.2 gauss/km. The strengths of fields in active groups within the chromosphere are of the same order of magnitude as in the lower photosphere. The agreement between the positions of flares and neutral points becomes even better in the chromospheric fields. Flares reduce the gradient around the neutral point, and sometimes destroy the poles adjacent to it as well as the neutral point itself. In general, the field is simplified by a flare (see Figure 7). The magnetic field in the solar atmosphere above active centers has greater continuity than in the photosphere, and may consist of a single vertical dipole. The intensity decreases rapidly with height[3] .

Gold and Hoyle proposed a model, in Volume 120 of the Monthly Notices of the Royal Astronomical Society (1960), in which the lines of force have the general shape of twisted loops protruding above the photosphere. When loops of opposite twist encounter each other, an explosive release of energy occurs, and thus a flare is generated.

A bipolar magnetic region (BMR) originates as though loops of the submerged toroidal field were brought to the surface. A magnetized region, a plage, and then a sunspot appear in that order.

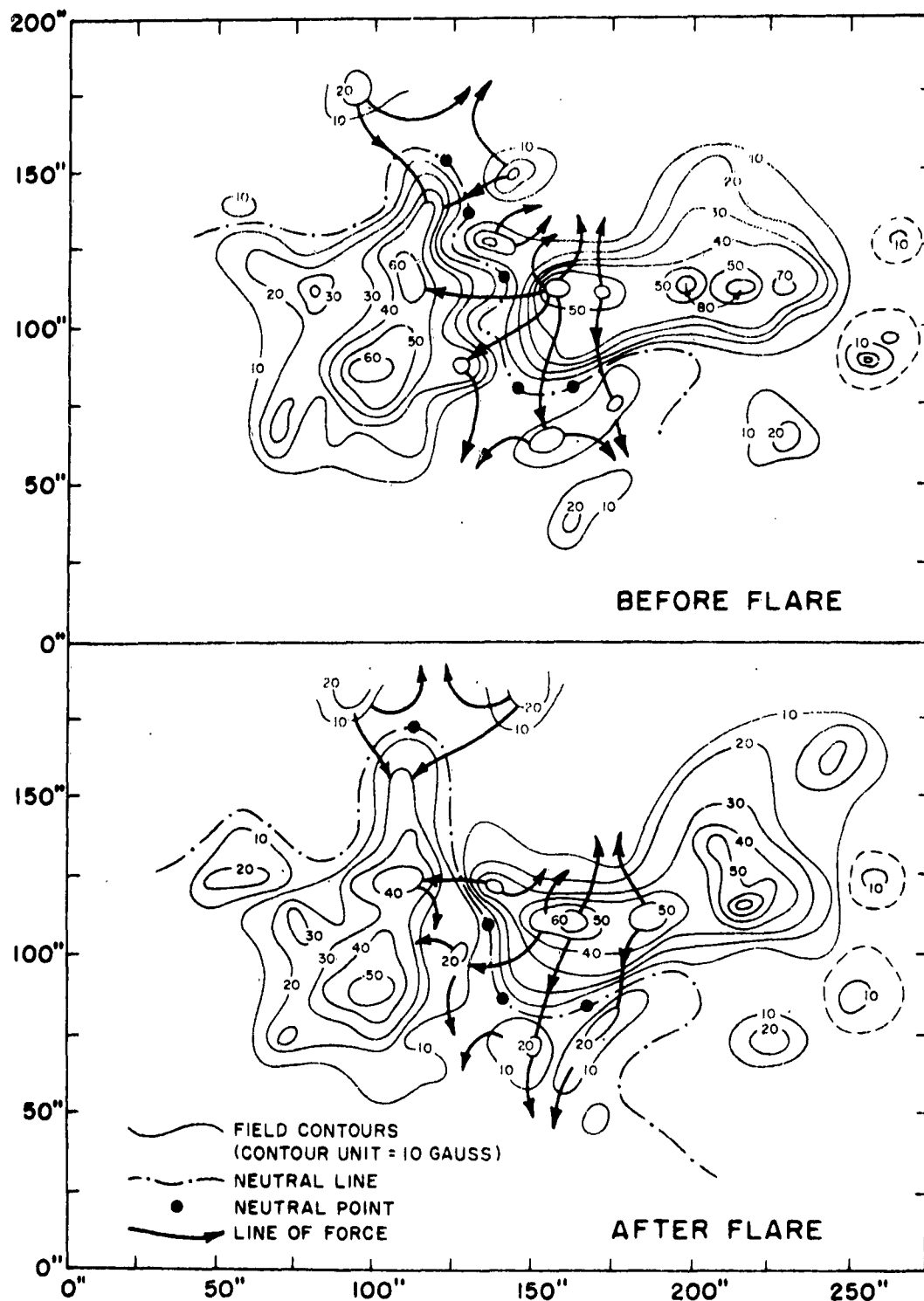


FIGURE 7. MAGNETIC FIELD OF A SPOT GROUP BEFORE AND AFTER A FLARE [2].

Eventually, the magnetic region expands and weakens, and the phenomena disappear in reverse order.

b. In Interplanetary Space.

The interplanetary field is formed by the outward streaming solar wind in which the field is imbedded. The field is radial near the sun because the inner corona rotates at nearly the same rate as the photosphere, but farther out the angular rotation is reduced and the stream appears to describe a curve that is convex toward the west. The strength of the interplanetary field is probably  $10^3$  gauss near the sun, but in the vicinity of the earth it has been measured at only  $2.5 \times 10^{-5}$  gauss during quiet sun and  $4 \times 10^{-4}$  gauss during active sun [1] .

The energy density or stress of a magnetic field is  $B^2/8\pi$  , where  $B$  is field strength in gauss. The corresponding expression for an ionized gas of density  $N/\text{cm}^3$  and absolute temperature  $T$  is  $2NkT$  where  $k$  is Boltzmann's constant ( $1.38044 \times 10^{-16}$  erg deg $^{-1}$ ). If  $B^2/8\pi > 2NkT$ , gas is constrained to flow along the lines of force, but if  $B^2/8\pi < 2NkT$  the gas will carry the field with it, particularly if the gas flow is perpendicular to the lines of force [9] .

Within about one or two radii of the sun  $B^2/8\pi > 2NkT$ , and the magnetic field partially guides coronal expansion, tending to concentrate the outward flow toward the equatorial plane. Far out in the interplanetary medium the situation is reversed. Using values for the strength of the interplanetary field obtained from Mariner II, it was found that in the region explored, the energy density of the plasma is much greater than the energy density of the magnetic field. This indicates that the magnetic field is carried into space by the plasma. Observations from Pioneer V showed that during an undisturbed period, the field between the sun and earth was perpendicular to the plane of the ecliptic.

Magnetic lines of force do not have ends and may be deformed without limit. For this reason, galactic or solar particles which move along paths in the magnetic field eventually have access to all portions of interplanetary space.

Near CA's the energy density of the field is greater than that of the plasma, and controls the plasma motions. Increase in coronal temperature above an active region produces an enormous outburst of solar gas. The expanding cloud of gas forms a shock wave of considerable strength, with a front up to  $10^4$  km in depth. The high velocity of the gas (plasma) draws out the field, causing a jog in

the lines of force, wherein the field density is increased by as much as a factor of ten. A long tongue of the sun's field may trail the shock wave. Arrival of the shock wave at the earth triggers the "sudden commencement" of a magnetic storm.

The lines of force tend first to diverge and then to converge, forming a "magnetic bottle" which was first described by Thomas Gold [38]. High-energy protons and electrons tend to follow a spiral path along the lines of force and are trapped inside the "Gold" bottle. When the earth passes through the bottle, the particles propagate directly to the earth and arrive in a short time; otherwise, those which reach the earth must do so over a more circuitous route and are delayed.

Parker and Piddington have proposed that the solar magnetic field is stretched out almost radially inside a shell of disordered magnetic field. Solar flare protons emitted from a corresponding position on the sun may travel directly to earth along the nearly radial lines of the field. Protons emitted elsewhere must reach the earth by diffusion through the interplanetary field.

Beyond the earth, the field becomes irregular, causing backward scatter of cosmic rays and isotropic flux. An alternative theory by Anderson and others requires, in addition, a storage region near the sun from which trapped solar protons are slowly released [16]. The storage of solar cosmic ray particles can be explained by suitable models of the interplanetary magnetic fields, but present knowledge does not allow a decision as to which model, or combination of them, is correct.

Most of the active regions which produce flares occur between  $10^{\circ}$  and  $30^{\circ}$  heliocentric latitude, and geomagnetic disturbances are most frequent when the earth intersects the lines of force emanating from those latitudes. This occurs during the spring and autumn, centered on the equinoxes. Around the time of solstice, when the earth is opposite the solar equator, disturbances are generally absent.

K. G. McCracken [47] has shown that the axis of symmetry of proton beams from two solar flares was inclined  $10^{\circ}$  north and  $50^{\circ}$  west of the sun. The particles were trapped in a magnetic configuration produced by the flare, as described above. But because of the sun's rotation, the lines of force curved to the right in the plane of the ecliptic. Thus the earth was connected to the lines of force which emanated from the western limb of the sun, and only particles produced near the western limb could reach the earth directly.

In addition to the interplanetary field effect on solar protons,

some effect is produced by the general bipolar field of the Galaxy, which is aligned on its major axis at an angle of  $55^\circ$  with the plane of the ecliptic [27].

## 5. Radio Emission.

The propagation of electromagnetic radiation is controlled by the electron density. Accordingly, solar radio emission originates entirely in the ionized solar atmosphere, where the concentration of free electrons is sufficient to reflect and absorb radio waves. On the central parts of the quiet sun, radiation of a given frequency originates in a thin layer just outside the critical level at which the electron density reduces the refractive index to zero. Since the electron density at various heights in the solar atmosphere is known, it is possible to estimate the height of the layer from which radio emission of a given frequency was produced. It is thought that the rising gas from a flare generates a radio disturbance at the local characteristic frequency of each level. The velocity of the disturbance is thus deduced from a knowledge of the electron densities in the corona and the rate of change of radio frequency with time.

Present radio telescopes do not have sufficient resolving power to describe solar radio sources in detail. Centimeter wavelengths originate at the  $10^4$  OK level in the chromosphere, decimeter waves in the inner corona, and meter waves at several hundred thousand kilometers in the corona. The intensity of radio emission varies over a broad time spectrum from irregular periods of seconds to cyclic periods of years.

### a. Continuous.

The radio sun shows a uniform disk at wavelengths of 1 cm, limb brightening at 3 cm, and limb darkening at meter wavelengths [12]. The sun is rarely quiet, and bright regions (radio condensations) can be observed at centimeter and decimeter wavelengths almost all the time. The 10.7-cm (2800 Megacycles per second) solar radio noise consists of a constant thermal component originating from the whole sun, and a slowly varying component identified with plages and coronal streamers [19]. The latter can have an intensity two to three times the constant component at sunspot maximum [15]. It varies by a factor of two over the 27-day solar rotation period, and also varies over the sunspot cycle so that at solar maximum it has an intensity two to three times the constant component. The 10.7-cm radio noise has an almost one-to-one correlation with the Greenwich sunspot areas [67], and thus has been shown to be an excellent indicator of solar spottedness or overall solar activity. Solar indices will be discussed at some length in a later section. As an example

of the appearance of the radio sun, Figure 8 shows the sun at 21-cm wavelength.

The source of continuous radio emission is apparently thermal radiation from areas of high density and temperature centered over plages at about 40,000 km height in the chromosphere and in the lower corona. Emission is explained by the acceleration of free electrons at encounters with positive ions [19]. The sources cover 1/6 to 1/3 of the area of the solar disk and normally last several months, well beyond the life of the associated CA's. Smaller transient features appear at wavelengths of 1 to 10 centimeters, with diameters about 1/30 of the solar disk and lifetimes of several hours or days. At millimeter wavelengths, emission intensity corresponds to that of a stable thermal source at  $10^4$  OK with occasional slight increases at the time of large flares.

b. Bursts.

The variable components, or bursts, of radio emission are closely associated with CA's. At meter wavelengths, enhancements may exceed the thermal (continuous) level by a factor of  $10^4$  or more. Enhanced emission at wavelengths above a meter is speculatively attributed to various non-thermal processes:

(1) Theories of burst origin [12].

(a) Plasma oscillation

A plasma is roughly synonymous with a neutral ionized gaseous medium. A supersonic perturbation of the plasma causes the electrons to become excited. The electrons are displaced by a uniform distance from the protons, tend to return to the neutral zone, overshoot the equilibrium position, and in a series of such motions set up a sinusoidal oscillation at the plasma frequency.

(b) Synchrotron Radiation

Electrons traveling at nearly the speed of light enter the strong magnetic field above a sunspot. The electrons spiral around the lines of force and radiate electromagnetic energy in proportion to the square of their central acceleration.

(c) Cerenkov Radiation

This effect is produced when particles of very high energy penetrate a medium in which the velocity of light is slower



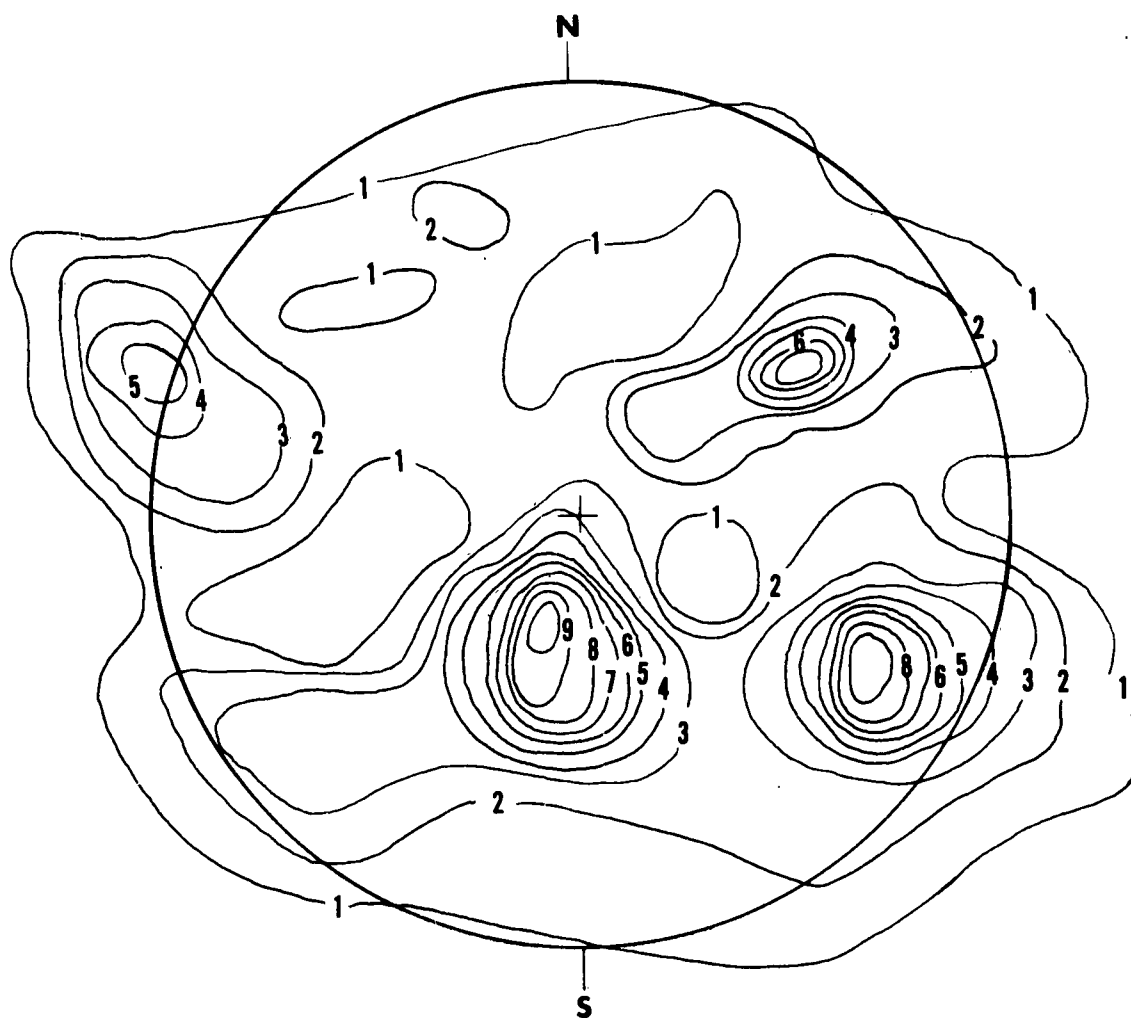


FIGURE 8. THE RADIO SUN AT 21 CM [12]

than their own velocity. This is possible only where the refractive index is greater than one. The particles are sharply decelerated and their excess energy is emitted as electromagnetic waves along a spreading cone.

## (2) Phases of radio events

There are two phases of the radio event which follow a solar flare. Immediately after the visible flare there is a series of short, intense bursts (Type III), which is occasionally followed at longer wavelengths by emission of longer duration (Type V bursts). In the second phase a large Type II burst is usually followed by a strong increase in radio flux which may last several hours (Type IV burst). Small flares may be followed by only a first phase. Table 5 gives a classification of radio noise bursts.

## (3) Types of bursts

(a) Type III, fast drift bursts, originate with brief, violent puffs which explode from the heart of a flare, but also occur when no flares are visible. Radiation increases to a series of sharp peaks, each with a duration of a few seconds. Each burst occurs on a narrow band at wavelengths on the order of 50 cm, then appears at successively longer wavelengths (lower frequency). The drift may be explained by a single disturbance which rises rapidly through the corona, exciting plasma oscillations whose characteristic frequency decreases with elevation. The frequency drift is 20 Mc/s, which corresponds to a source velocity  $1/3$  to  $1/2$  the speed of light. Type III bursts are negatively correlated with geomagnetic storms, which are due to slower moving particles (see Plate XX).

(b) Type V bursts are intense continuum emissions over a broad frequency range with durations of a few minutes or less (see Plate XX). They are explained by synchrotron emission over an extensive region in the outer corona. Types III and V may be produced by the same explosion. In some cases the electrons leave the corona, while in others they return to the photosphere along the lines of force and produce a U burst. U bursts are Type III's which reverse at around 150 Mc/s and drift back toward higher frequency. They may be generated by streams of particles which do not have enough energy to overcome the magnetic field and are drawn back into the sun (see Plate XXI).

(c) Type II bursts begin with an outburst which slowly moves toward lower frequency. The narrow peaks have a slow drift of  $1/\text{Mc/s}$ , indicating source velocities of 1000 to 1500 km/sec (see Plate XX). The source moves outward through the corona, emitting at the

Table 5. Classification of Solar Radio Emission (Adapted from [12] )

Burst Type	I	II	III	IV	V
	Noise bursts	Slow drift bursts or outbursts	Fast drift bursts	Continuum outbursts or storm-phase bursts	Centimeter bursts
Duration	Tenths of seconds	Minutes; complex	Seconds often in groups	Minutes to hours	Minutes
Size	Small (Minutes of arc)	?	Up to 10 minutes of arc? Increasing with wavelength	Up to 10 minutes of arc; increasing with wavelength	~50,000 km
Apparent Temperature	~10 <sup>9</sup> °K	< 10 <sup>11</sup> °K	> 10 <sup>11</sup> °K	~10 <sup>11</sup> °K	~10 <sup>11</sup> °K
Polarization	Circular	Usually not strongly polarized or unpolarized	Irregular but usually unpolarized	Often circularly polarized	Variable but sometimes elliptically polarized
Wavelengths	Bursts are at Meter wavelengths but associated centers often emit weak continuum	Centimeters to tens of meters: sweep in frequency at ~100 Mc/s; bandwidth ~50Mc/s	Meters to tens of meters; sweep in frequency at ~100 Mc/s; Bandwidth ~5Mc/s	Continuum from centimeters to tens of meters	Broad-band continuum but enhanced at centimeter wavelengths
Origin	Cerenkov?	Plasma oscillations	Plasma oscillation? synchrotron? Cerenkov?	Synchrotron	Synchrotron
Associated Phenomena	Associated with "R" centers" which are in corona and roughly overlie active regions. sources of ~1500 km/s in corona; due to shock wave; perhaps associated with magnetic storm producing corpuscles.	Exhibit harmonics; are associated with flares; usually follows start of flare; are moving sources of ~1500 km/s in corona; due to shock wave; perhaps associated with magnetic storm producing corpuscles.	Associated with early stages of flares; are probably sources moving at substantial fraction of speed of light; perhaps associated with proton showers at Earth.	Associated with certain very strong flares, starts ~15 min. after flash phase; cosmic ray associations; sources sometimes displace in atmosphere at speeds of 100-1000 km/s; often associated with Type II Bursts.	Ascending sources of speeds ~3000 km/s; often follow Type III Bursts.

Table 5. Continued

Burst Type	Quiet Sun	Slowly varying component	Noise storms
Duration	11 - year cycle?	Days to Months	Hours to Days
Size	$\geq 32$ minutes of arc, increasing with wavelength	As for spots and faculae	Small (minutes of arc)
Apparent Temperature	$< 10^6$ OK	$< 2 \times 10^6$ OK	$\sim 10^9$ OK
Polarization	Unpolarized	Unpolarized	Circularly polarized
Wavelengths	Centimeters to tens of meters	Centimeters to tens of meters?	Meter wavelengths
Origin	Thermal	Thermal	Cerenkov?
Associated Phenomena	None	Complex behavior on centimeter wavelengths with circular polarization	Simultaneous continuum and short bursts (Type I)

There are still other types of solar radio emissions such as U-bursts and inverted bursts, etc.

plasma frequency which decreases with the electron density. Sources near the limb move toward the limb and beyond. In all cases, Type II bursts follow the ejection of matter from a flare, but they are believed due to plasma oscillations excited by the shock wave which precedes the cloud of ejected particles.

(d) Type IV. Large Type II bursts are sometimes followed by a further increase in intensity (Type IV burst) lasting 10 minutes to a few hours. Type IV is a broad band, steady continuum emission and may cover the entire spectrum of radio frequencies, but particularly the centimeter wavelengths. The intensity of a Type IV burst is much greater than that of a noise storm (see below). Sources of Type IV emission have  $1/3$  the diameter of the solar disk. They appear in the corona at four or five solar radii. Type IV bursts can be explained by synchrotron radiation generated by relativistic electrons in the corona. Type IV events are rare, and seem to occur only when a significant portion of a spot umbra is covered by a flare.

There are at least three subtypes commonly distinguished by radio astronomers[28]: IV-A is continuum emission at centimeter and decimeter wavelengths, IV-B is the "classical" Type IV emission at meter and decameter wavelengths which was first discovered by A. Boischot who investigated its properties[22], and IV-C is a noise storm continuum at meter and decameter wavelengths emitted from sources with small diameters (a few minutes of arc) but having durations of a few hours to some days[12]. These three types have been summarized by Kundu and Smerd[44] as shown in Table 6.

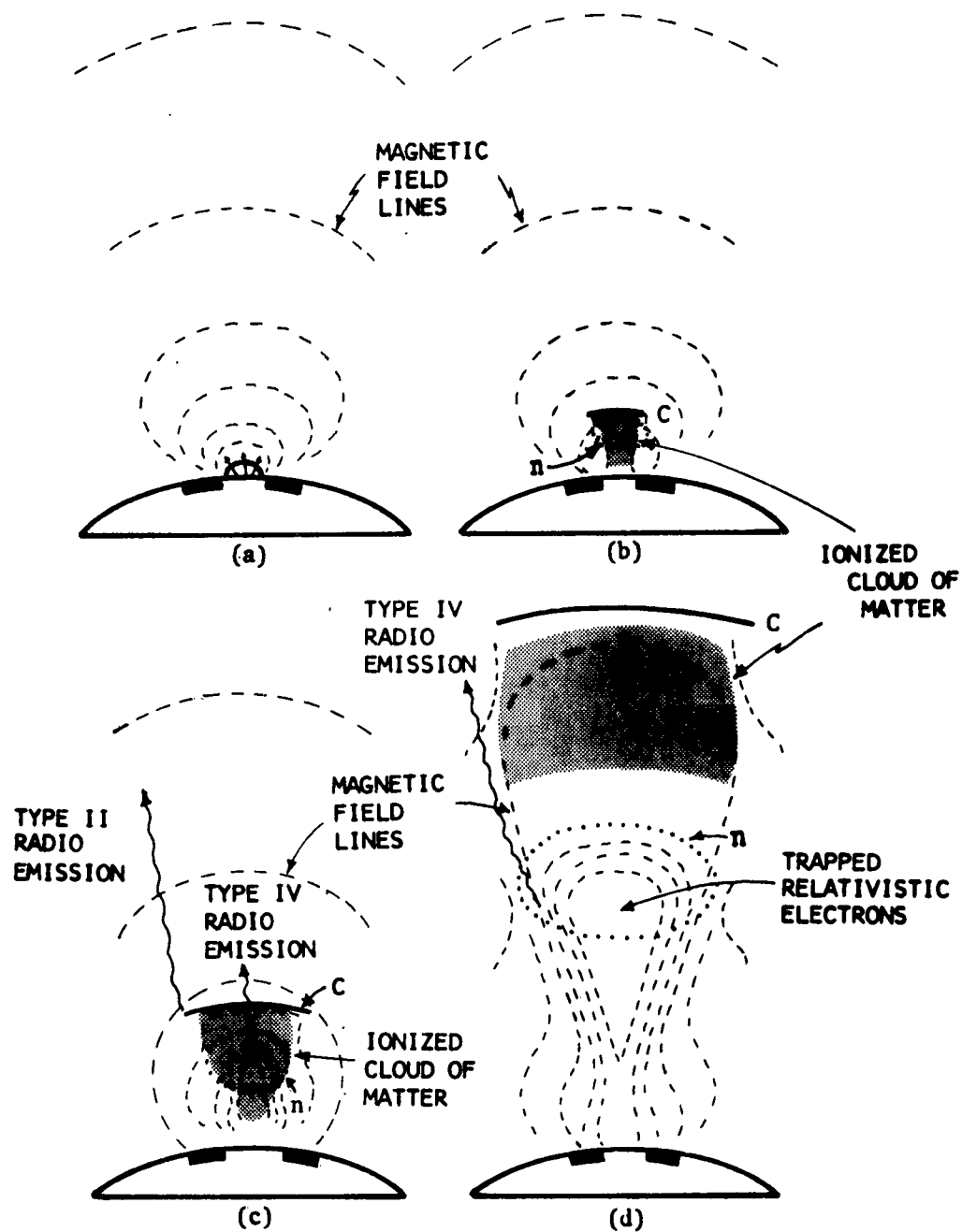
Type II and IV radio bursts are caused when an initial explosion ejects high-energy electrons and a mass of much slower material (see Figure 9, part (a)). The jet of matter rises, preceded by a shock wave, C, and since the matter is highly ionized, takes with it part of the magnetic field, n, of the sunspot group (Fig 9, (b)). The electrons are captured by the field and cannot escape. The jet of matter continues to rise, dragging with it the cloud of electrons (c). The shock wave generates Type II emission and the trapped particles, accelerated by the magnetic fields, generate Type IV emission. The shock wave and ionized matter go out into space, while the cloud of relativistic electrons comes to rest in the outer corona and continues to emit synchrotron radiation for several hours (d).

(e) Noise storms and Type I bursts

Radio noise storms consist of a slowly varying background with a narrow bandwidth of 5 to 30 Mc/s at wavelengths of

Table 6. Characteristics of Type IV Radio Burst Subtypes [44]

	IV-A	IV-B	IV-C
Spectral Range	10,000 to ~ 20,000 Mc/s	~250 to 25 Mc/s	~1000 to 25 Mc.s (the upper frequency limit is uncertain)
Beginning	At or near start of flare	Usually within minutes of a type II burst; after maximum	Following a Type IV-B
Duration	Several tens of minutes	Several tens of minutes	Hours (possibly days)
Polarization	Partially cir- cular	Partially circu- lar	Strongly circular
Location	In bright region near flare	Well away (up to several solar radii) from flare after initial movement	Closer to flare (a fraction of a solar radius) than IV-B
Source Size	Small (< 5 min- utes of arc)	Large (~10 minutes of arc)	Small (a few minutes of arc)
Directivity	Little	Little	Strong toward the center
Movement	Not appreciable	Early Large-Scale movement away from flares at speeds of several 1000 km/sec	None



**FIGURE 9. STAGES OF A SOLAR EXPLOSION**  
[ADAPTED FROM REF 12]

one to five meters, upon which are superimposed Type I bursts lasting about 0.2 seconds to a minute. The frequencies drift toward higher or lower values depending on the position and direction of the motion of the source. Noise storms occur within a half-hour after the onset of 25% to 30% of Importance 2 flares, and more frequently following larger and brighter flares [64]. Many flares, even large ones, are not followed by noise storms, and in some cases existing storms decrease with the appearance of a flare. Certain plage regions, and large sunspots with high magnetic field strength, are more likely to produce storms than others. Type I bursts occur within 15 minutes of the flares which produce them. Noise storms last one to five days and may be so severe that they jam radars on meter wavelengths. Emission on longer wavelengths, 15 to 20 meters, occurs less frequently and has a shorter duration. Noise storm sources, or R regions, are found at  $1/3$  to 1 solar radius above optically active regions, usually complex sunspot groups, and have diameters of 6 minutes of arc [19]. They are attributed to either plasma oscillation or gyro-magnetic radiation, and usually occur above active regions that are also producing Type IV bursts. R regions rotate with the sun, but at a different rate from photospheric elements. Emission is strongest near the central meridian.

(f) Polar cap absorption (PCA) and polar blackout

Several hours after the onset of a flare which produces sudden ionospheric disturbances (SID's) and Type IV radio bursts, in the polar regions there sometimes occurs almost complete absorption of cosmic radio noise at 27 Mc/s due to increased ionization in a layer about 50-90 km above the surface of the earth. This effect is termed "PCA". Polar blackouts are similar but have the effect of sudden short wave fades. These effects are apparently due to protons with energies 10-100 Mev (subcosmic rays) which enter the atmosphere at latitudes 60-65°. These particles are more energetic than those which produce geomagnetic storms [1]. PCA's and polar blackouts are similar in effect but different in character. PCA's occur up to a few hours after a flare whereas polar blackouts occur as late as 24 hours after the onset of a flare. The time of maximum PCA occurs only during the day whereas the time of maximum for the polar blackouts occurs only at night. PCA's precede auroral activity as much as one to two days. Auroras occur simultaneously with polar blackouts.

## 6. Solar Effects

The important variable effects of the sun on the earth and its atmosphere are produced by blasts of corpuscular or electromagnetic radiation from active sunspot regions, and particularly from flares-- both large and small - which occur in the active regions. A basic



difference in the effects of the two types of radiation is that particles (corpuscular radiation) are deflected by the magnetic fields of the earth and space and may reach both the light and dark hemispheres, tending to be concentrated by the lines of force in the polar regions, while electromagnetic waves are not significantly affected by the fields and in general influence only the daylight hemisphere. The surface of the earth is protected from most flare radiation by the atmosphere, which provides the equivalent of 1000 gm/cm<sup>3</sup> of shielding. The approximate time sequence of various flare effects is shown in Figure 10.

#### a. Solar wind

The solar wind is generally considered to be a continuous outflow of plasma, or highly ionized gas, from the sun. However, there are few direct indications of its existence, and divergent views concerning its speed and persistence. Until recently the most acceptable values were a density of 10 protons or electrons per cubic centimeter at the earth's orbit, a velocity of 300 km/sec [67] and a proton energy of 0.5 Kev. Scattering of sunlight from space indicates a coronal density of 10<sup>2</sup> particles per cubic centimeter and a velocity of 500 km/sec [9]. Under disturbed solar conditions, density has been estimated as 100 particles per cubic centimeter, velocity as 1500 km/sec, and energy as 10 Kev. The bending of comet tails indicates a similar velocity. Direct observations from Mariner II has given plasma velocities of 400 to 700 km/sec, on the basis of assumed ion densities of 2.5 to 4.5 particles per cubic centimeter. Observations made by Explorer X have given a normal density in the solar wind of 10 particles per cubic centimeter and velocities ranging from 275 km/sec during quiet sun to 1600 km/sec after a major solar flare.

After a flare on one occasion, solar protons were observed to have a velocity of more than 10<sup>5</sup> km/sec. The sudden commencement of the stream of very high energy particles reaching earth occurred less than two minutes after the observed onset of the flare. Violent agitation of the interplanetary field began about five hours after the onset of the flare.

Using values of interplanetary field strength obtained from Mariner II, it is found that in space near the earth the energy density of the plasma is greater than that of the magnetic field. This indicates that the magnetic field is carried along by the plasma. Thus the magnetic field of the sun must extend as far as the solar wind.

One effect of the solar wind is to bend the tails of comets away from the sun. Light pressure from the sun is not enough to

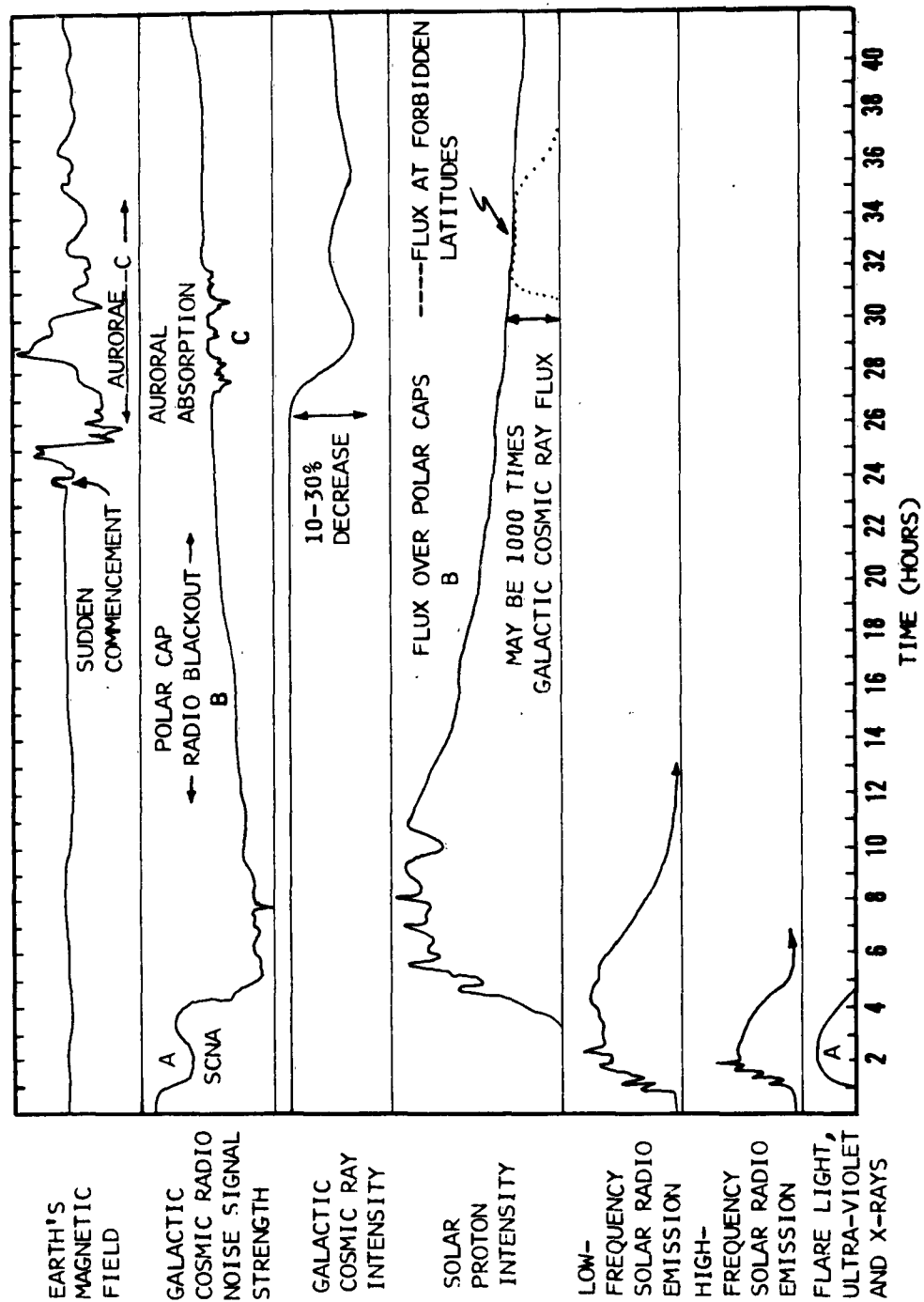


FIGURE 10. TIME SEQUENCE OF FLARE EFFECTS [15]

completely explain this effect. Another effect is to compress the geomagnetic field on the side of the earth toward the sun, and extend it in a long tail on the shaded side. The dynamic pressure of the solar wind is about  $10^{-9}$  to  $10^{-7}$  dynes/cm<sup>2</sup>, while the pressure caused by the sun's visible light is  $4.7 \times 10^{-5}$  dynes/cm<sup>2</sup> at the earth's orbit.

#### b. Solar particles

From a few minutes to several hours following the appearance of some solar flares, protons with energies ranging typically up to 200 Mev, but occasionally up to 24 Bev[9], and electrons with energies up to 100 Mev, are detected at the earth, usually in the polar regions inside the auroral zones. Particle density is only about  $10^{-11}$ /cm<sup>3</sup> at the earth. Proton radiation is observed by a riometer, which measures proton beams indirectly by the effect on the absorption of cosmic radio noise. The riometer (relative ionospheric opacity meter) measures the variation of galactic cosmic radio noise in decibels.

The rigidity a particle requires to penetrate the earth's field varies inversely with latitude. Rigidity is defined by:

$$N = p c / Ze$$

where  $p$  is the particle momentum,  $c$  is the velocity of light,  $Ze$  is the particle charge, and  $N$  is rigidity in Bev. All particles of the same rigidity undergo the same deflection by a given geomagnetic field strength. Hence, measurements at various latitudes provide a key to the distribution of the energies of protons emitted from a given source on the sun[1].

A solar flare emits a great number of particles covering a broad spectrum of particle energies. On the low energy side is a large cloud of relatively low-energy particles (30 to 100 Mev); on the high energy side a much smaller number of very high energy protons and electrons, or solar cosmic rays. After the flare of February 23, 1956 particles were detected which had energies above 30 Bev.

The lower energy particles arrive at the earth's outer atmosphere as frequently from the eastern as from the western portion of the sun, while the high energy particles normally reach the earth only if the source is near the western limb[12]. Because of their great density in the emitted cloud, the low-energy particles have a higher kinetic energy than the interplanetary field (see Section 4) and carry the lines of force with them. A magnetic tube or bottle is created which extends beyond the earth in a long curve due to the sun's rotation, and may be maintained for some time over an active sunspot region by the repeated ejection of low-energy particles (see Figure 11). These particles travel at speeds of 1000 to 2000 km/sec, and take several

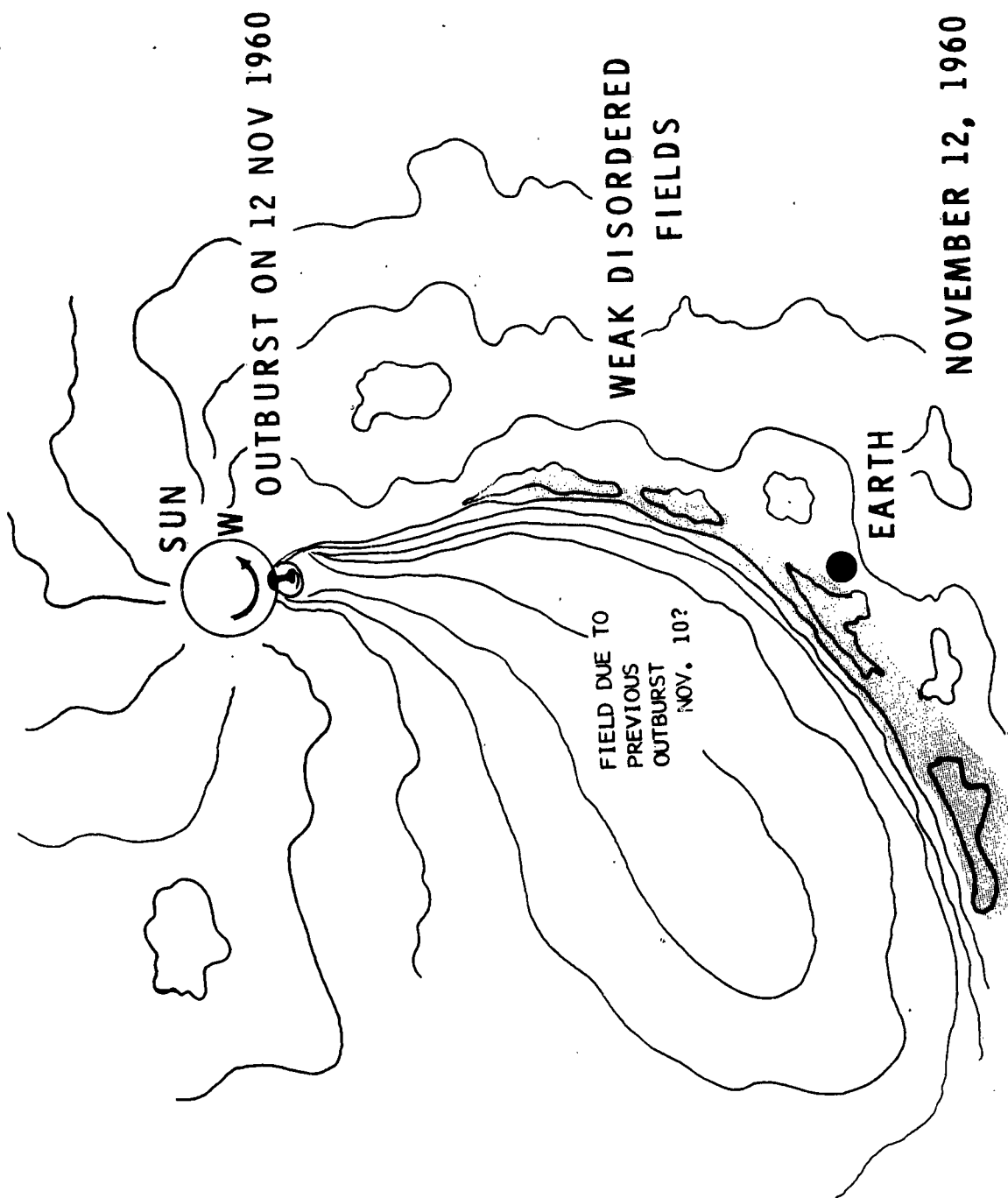


FIGURE 11. SCHEMATIC DIAGRAM OF THE MAGNETIC FIELDS IN THE INNER SOLAR SYSTEM AT 1330 U.T. ON NOVEMBER 12. THE MAGNETIC LOOPS ATTACHED TO THE SUN ARE SUPPOSED TO EXIST BUT DO NOT ESSENTIALLY LIE IN THE PLANE OF THE PAPER. THE LOOPS CONSTITUTE A 'MAGNETIC BOTTLE'. THE SHADED AREA REPRESENTS REGIONS OF CHAOTIC FIELDS.

hours to reach the vicinity of the earth. They increase the ionization of the upper atmosphere and cause polar cap absorption (PCA) of cosmic radio noise, but are decelerated and/or recombined before they reach the surface. If a large flare now occurs in the active region, relativistic protons and electrons will be produced, which, despite their high energy, occur in such low concentrations that their paths are controlled by the lines of force. They travel inside the magnetic bottle, and provided that the season is near the spring or fall equinox and that the originating sunspot region is near the western limb of the sun, the bottle may intercept the earth. In this case, the particles will reach the earth within a few minutes (see Figure 12).

Solar flare events may be divided into two classes, according to whether they contain relativistic protons or not. Relativistic or solar cosmic ray events are defined by proton energies of 1 Bev or greater, and reach the earth's surface. Most large solar flares emit protons, about 50 cases having been detected over a seven-year period, but only 10 over the period 1942-1960 were relativistic. The largest of these was that of February 1956, in which the flux above 3 Bev was estimated at 300 times normal cosmic ray intensity.

The occurrence of relativistic events shows no apparent correlation with the solar cycle, except that they have not been observed to occur at solar minimum. The non-relativistic particle radiation from solar flares occurs principally during years of sunspot maximum. These events are further divided into two classes by a maximum flux of  $10^4$  protons/cm<sup>2</sup>/sec (large) and  $10^2$  protons/cm<sup>2</sup>/sec (small) within the geomagnetic field. The two classes do not seem to occur in any fixed ratio. Beyond the earth's field, flare radiation could have an intense low energy component, or an important electron flux component, which has not been measured by space probes.

Detectors in different locations respond to different energies, the highest energies arriving first. The time of release to maximum intensity at earth is about 10 to 30 minutes. There is a brief transition as particles begin to arrive from directions other than the source; gradually, isotropy\* is established and energy is no longer released from the flare region, but the influx of particles continues for one to three days. One explanation is that the sun accelerates particles over only a short period of time, but the lower energy particles are temporarily trapped in interplanetary magnetic fields. The early arrival of high energy particles is explained by a tongue of a nearly radial field connecting the sun and earth (see Figure 12). In the tongue, the field is fairly

\*Isotropy: Radiation equal from all directions.



Plate I. Photospheric granulation showing small pores (small black spots) which could develop into sunspots (Sac. Peak Obs.)



Plate II. Inner corona seen during the total eclipse of 14 Jan 26. This intermediate type of corona is seen between solar minimum and maximum. Note solar limb prominences. (U.S. Navy)

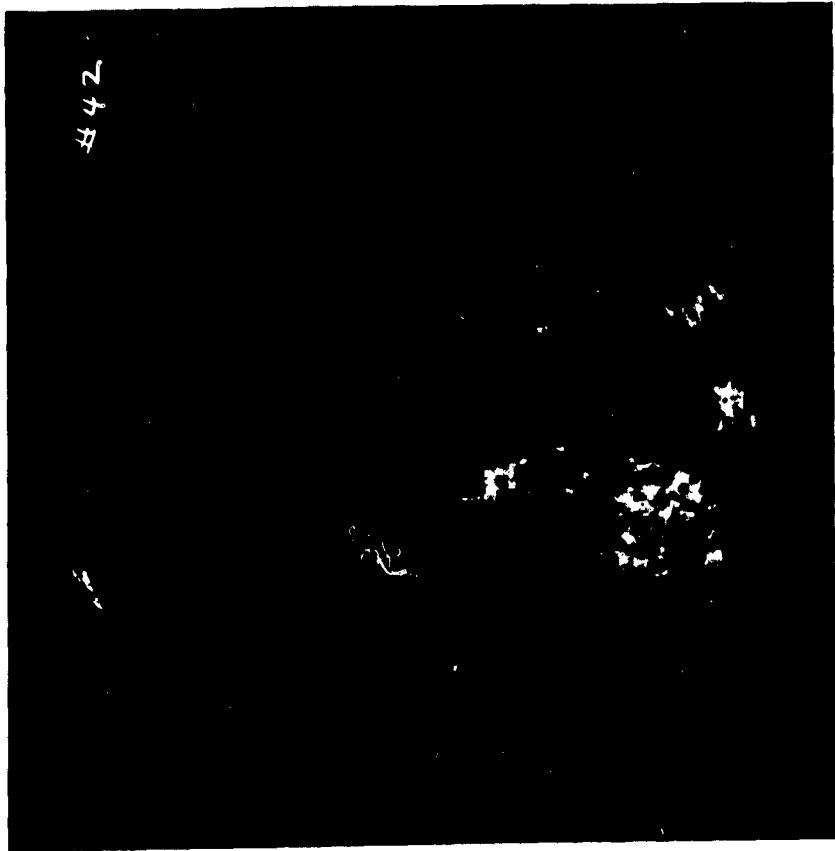
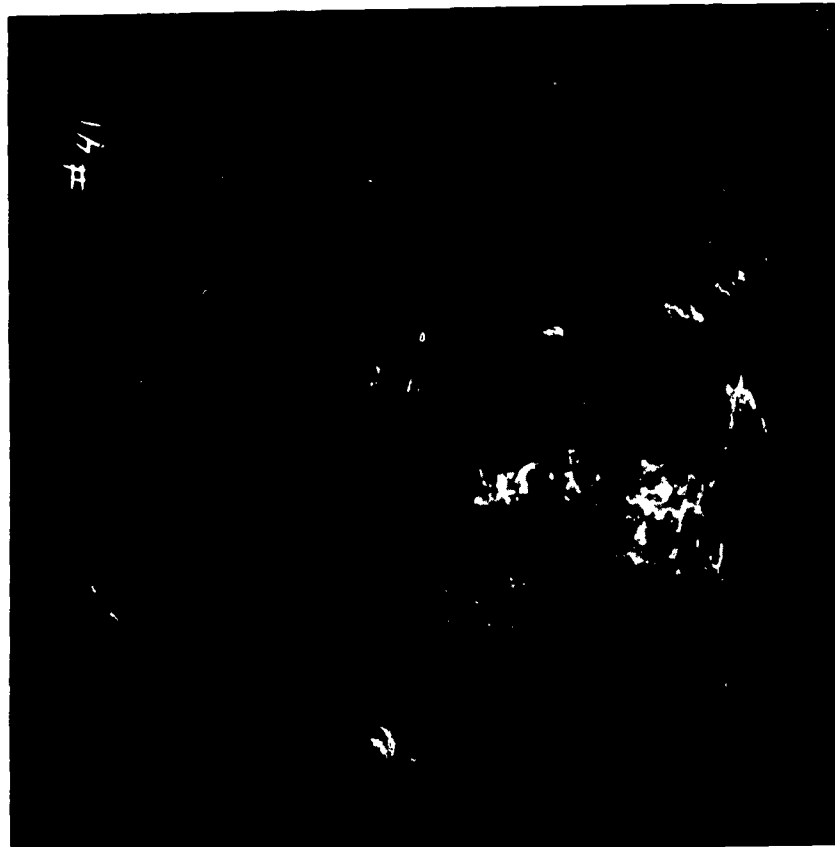


Plate III. The solar chromosphere in the Balmer alpha light of hydrogen (#41) and light of calcium (#42). Both views were taken on 6 Sep 60. Note the dark filaments visible on #41 are not visible on #42, whereas the plages are generally quite visible on both. Note on #41 the small limb prominence in the upper left hand corner which becomes a dark filament on the disk.





PLATE IV. The short, sharp spikes in the lower left, are chromospheric spicules seen on the solar limb. The tree like shape on the right is termed a "Tree Trunk" (ANb) prominence. (SAC. Peak Obs.)

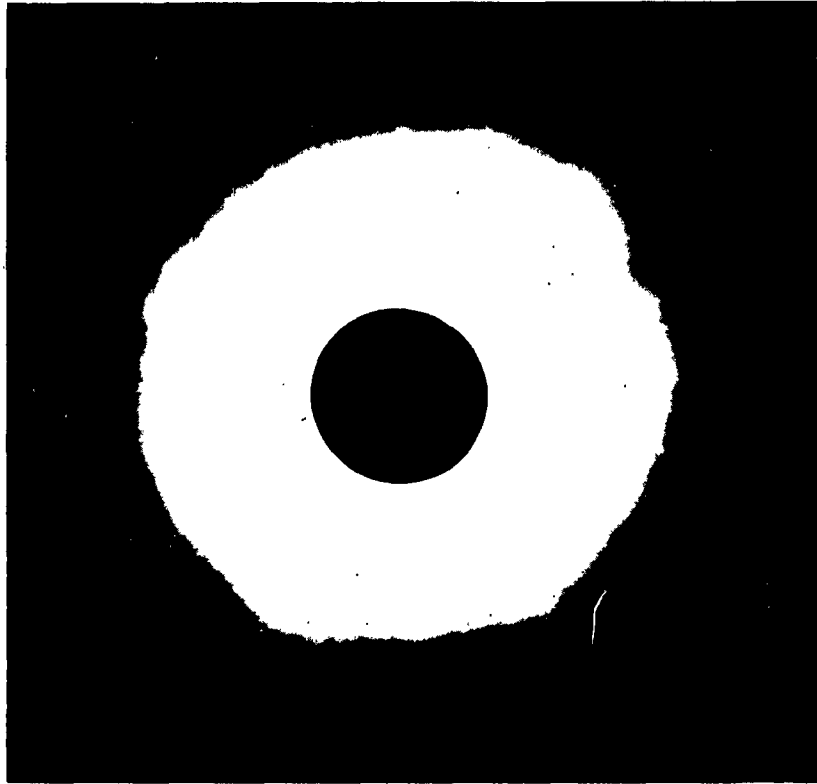


Plate V. Solar corona near solar maximum. Note the symmetrical shape of the corona. Near solar minimum the corona is assymetrical. (Sky and Telescope)



Plate VI. Sunspots showing umbrae, penumbrae and granulation. (Proj. Stratoscope - M. Schwartzchild)



Plate VII. Bright faculae seen near the solar limb. Sunspots, umbrae, and penumbrae are clearly seen in this 13 Feb 56 photo of the solar photosphere. (Mt. Wilson)



Plate VIII. Moustache. The bright triangular area near the center of the large spot group is the moustache. The name is derived from the shape of the spectrum. (Sac. Peak Obs.)

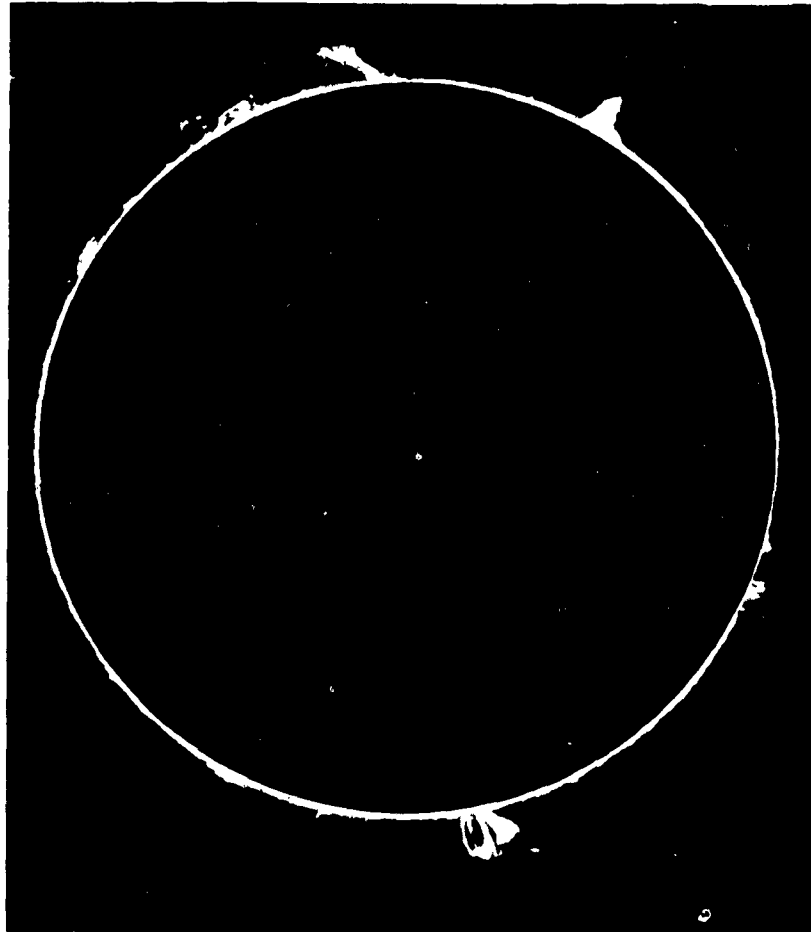
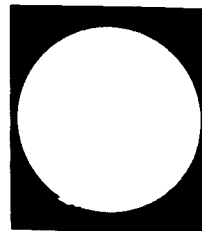
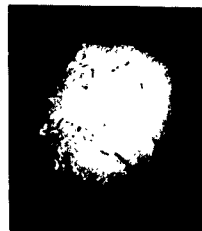


Plate IX. Limb prominences taken with a coronagraph. (Sky and Telescope)

# DISK PASSAGE OF A LARGE PROMINENCE



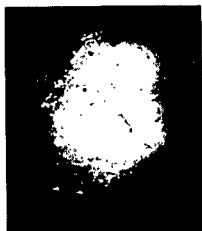
22 JAN. 59



24 JAN.



25 JAN.



26 JAN.



27 JAN.



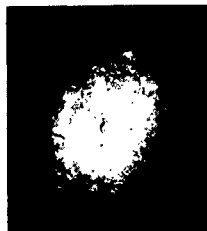
28 JAN.



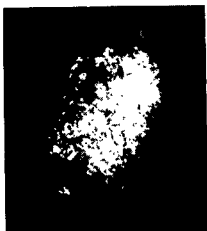
29 JAN.



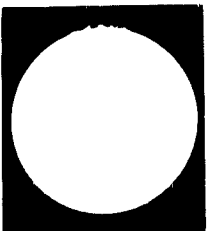
30 JAN.



31 JAN.



2 FEB. 59



4 FEB.

## ERUPTION AT WEST LIMB



Plate X. Disk passage of a large prominence. Note that the limb prominence visible in the 22 Jan and 4 Feb photos is the long, dark filament visible in the other sequence photos. (Sac. Peak Obs.)

## PROMINENCE ERUPTS 5 FEB. 59





Plate XI. A quiescent prominence which is termed a hedgerow. Note the fine structure of radial filaments. (Sac. Peak Obs.)





Plate XII. An eruptive prominence. Note the white dot to the right--it represents the earth to scale. (U.S. Navy)

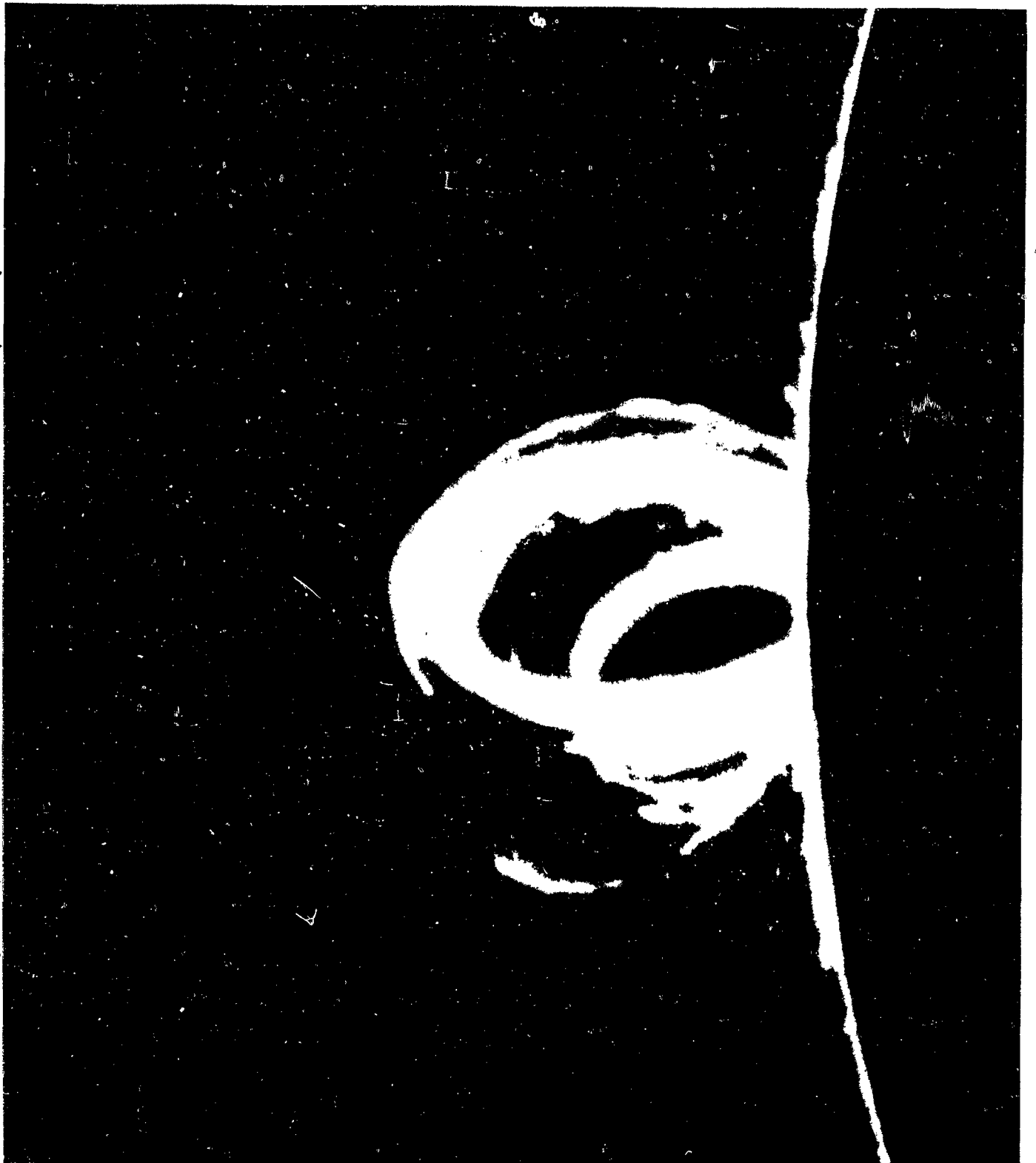


Plate XIII. A loop prominence. These are often associated with sunspots.  
(Sac. Peak Obs.)

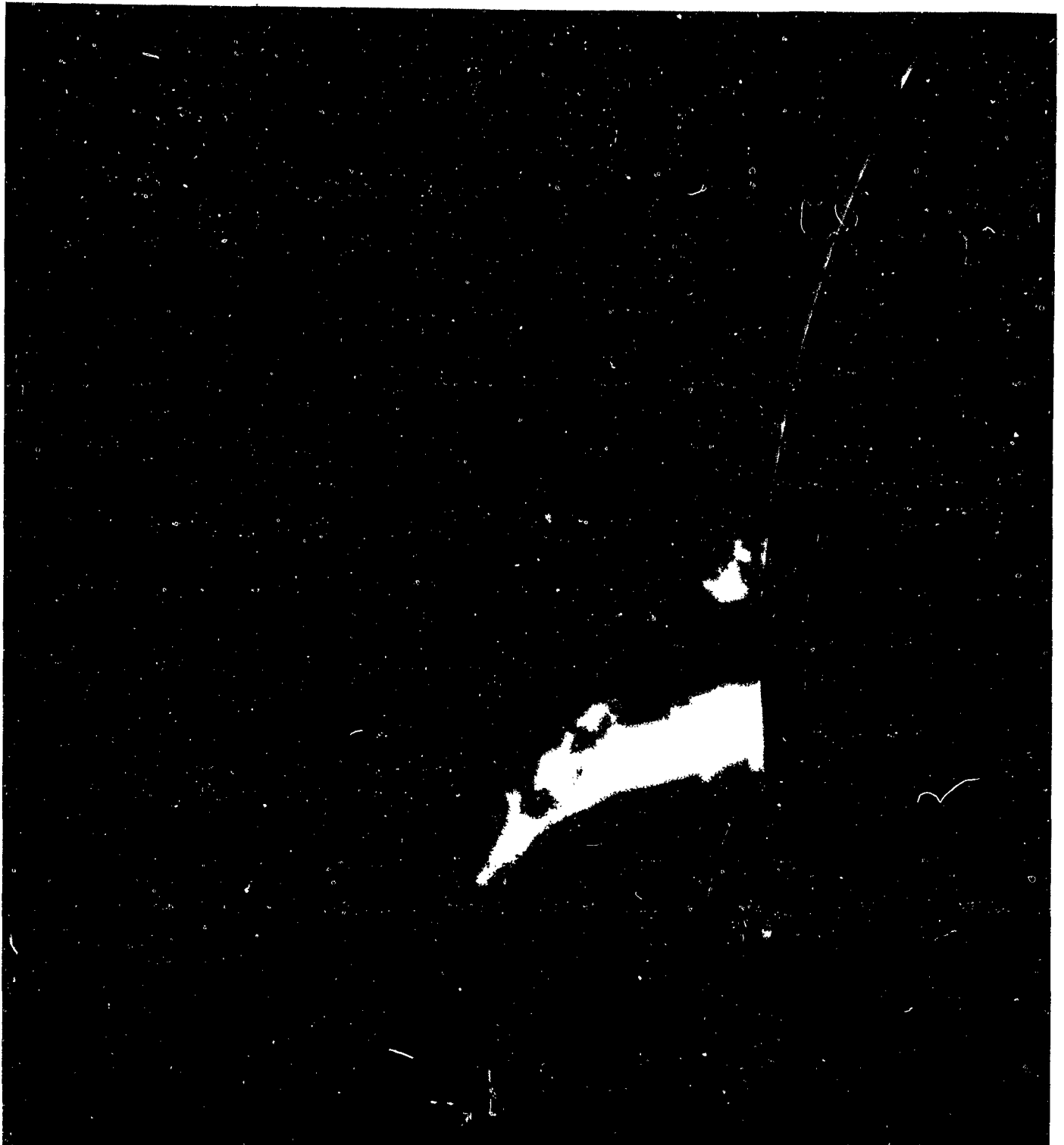


Plate XIV. A surge prominence. Often associated with sunspots or active regions, these prominences eject material from the sun along a magnetic line of force. Some of this material cannot escape and falls back along the same trajectory as it was ejected. (Sac. Peak Obs.)

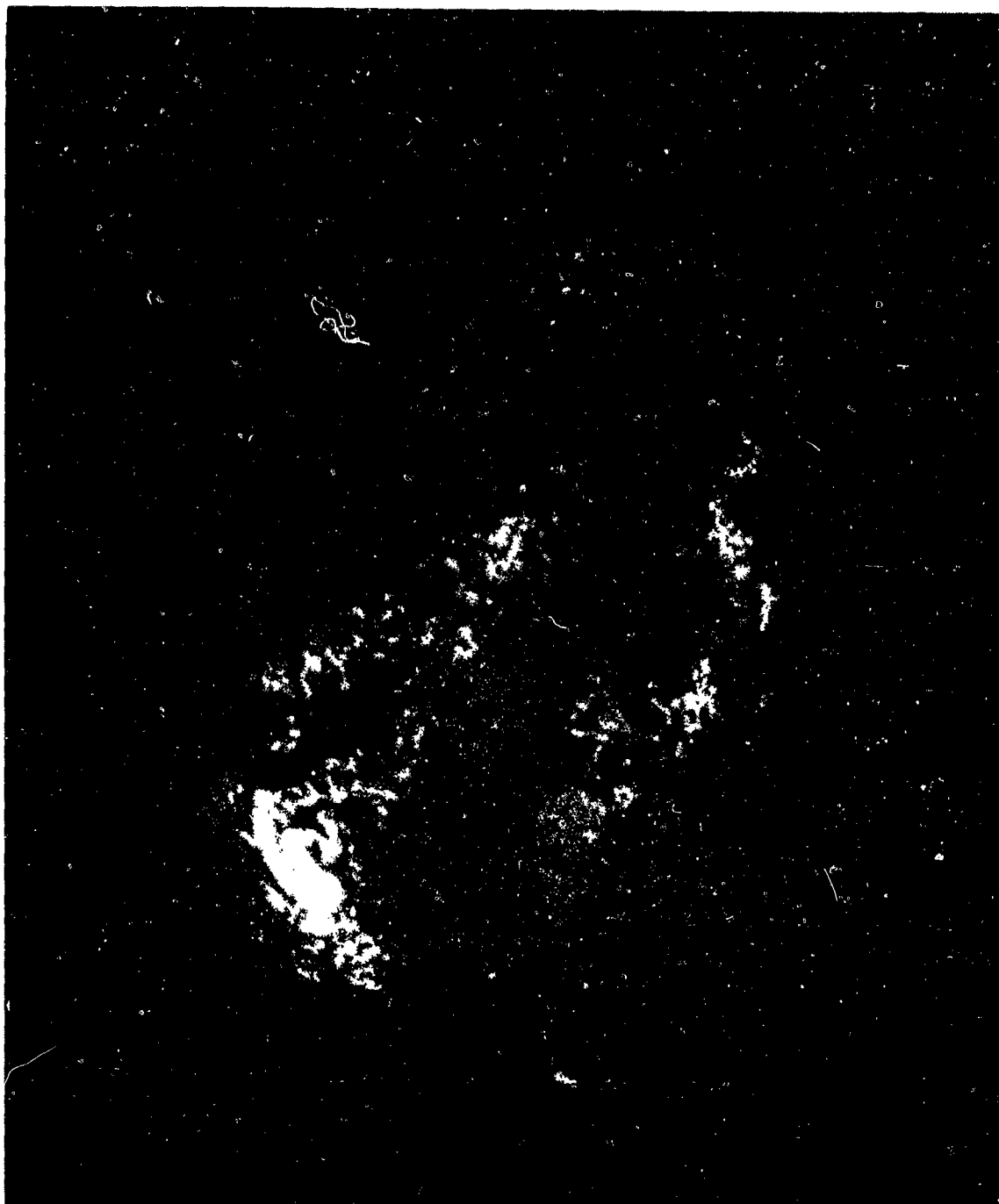


Plate XV. The solar chromosphere in the Balmer alpha light of hydrogen.  
A class 3+ flare is in progress in this 10 May 59 photograph  
taken about 2200 UT. (Sat. Peak Obs.)

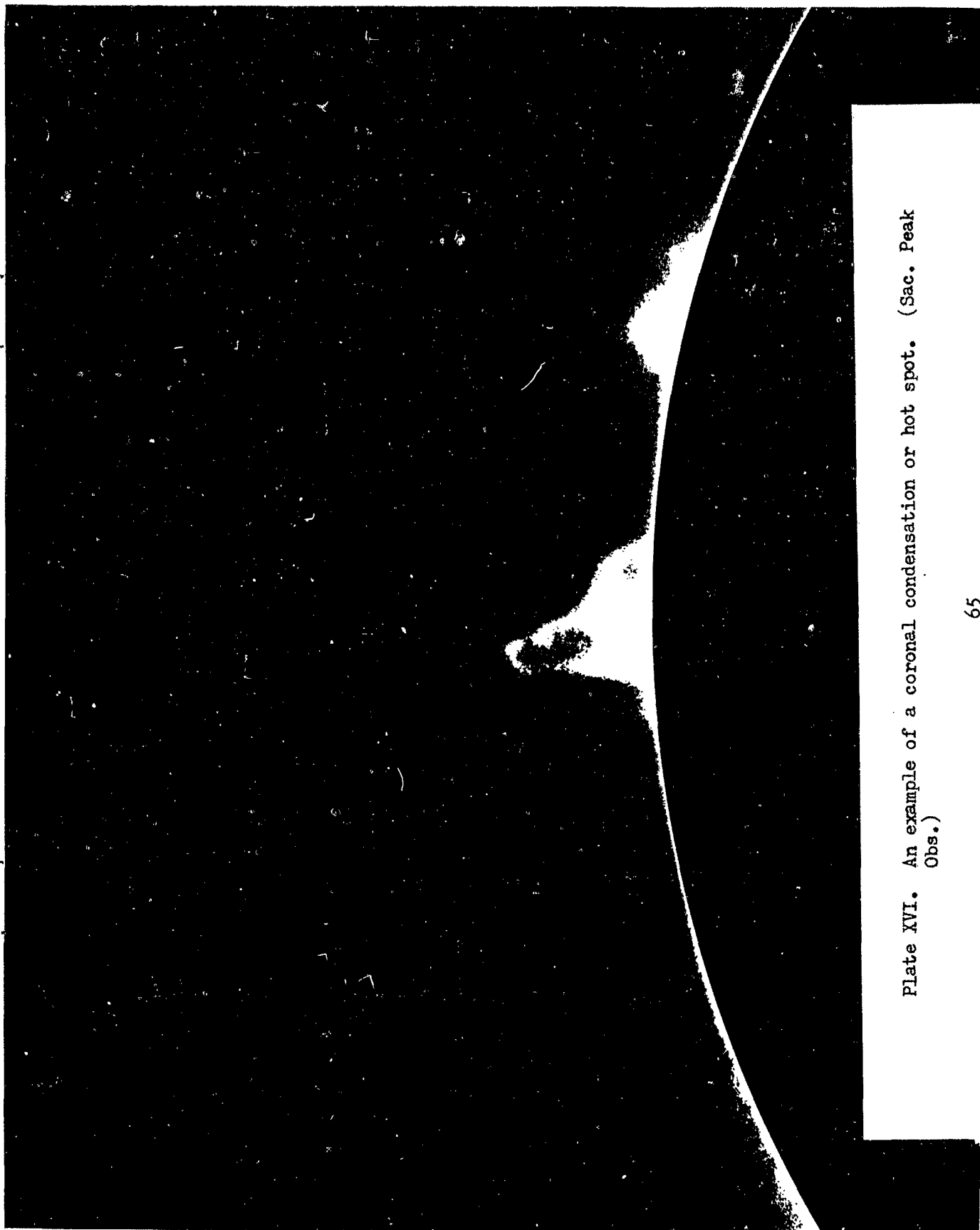


Plate XVI. An example of a coronal condensation or hot spot. (Sac. Peak  
Obs.)

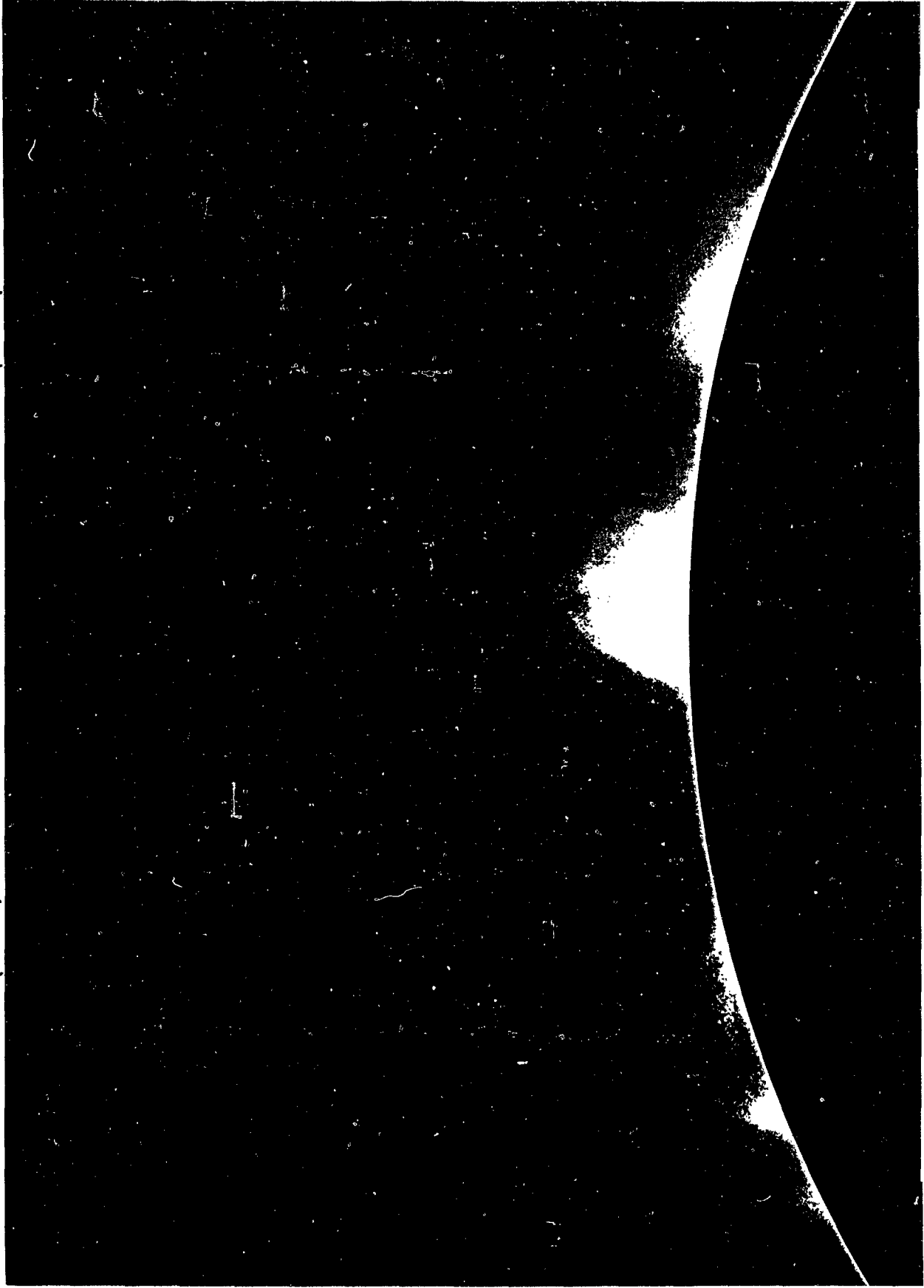


Plate XVII. Example of coronal loops or arches. (Sac. Peak Obs.)



Plate XVIII. Example of a coronal fan showing curved rays. (Sac. Peak Obs.)

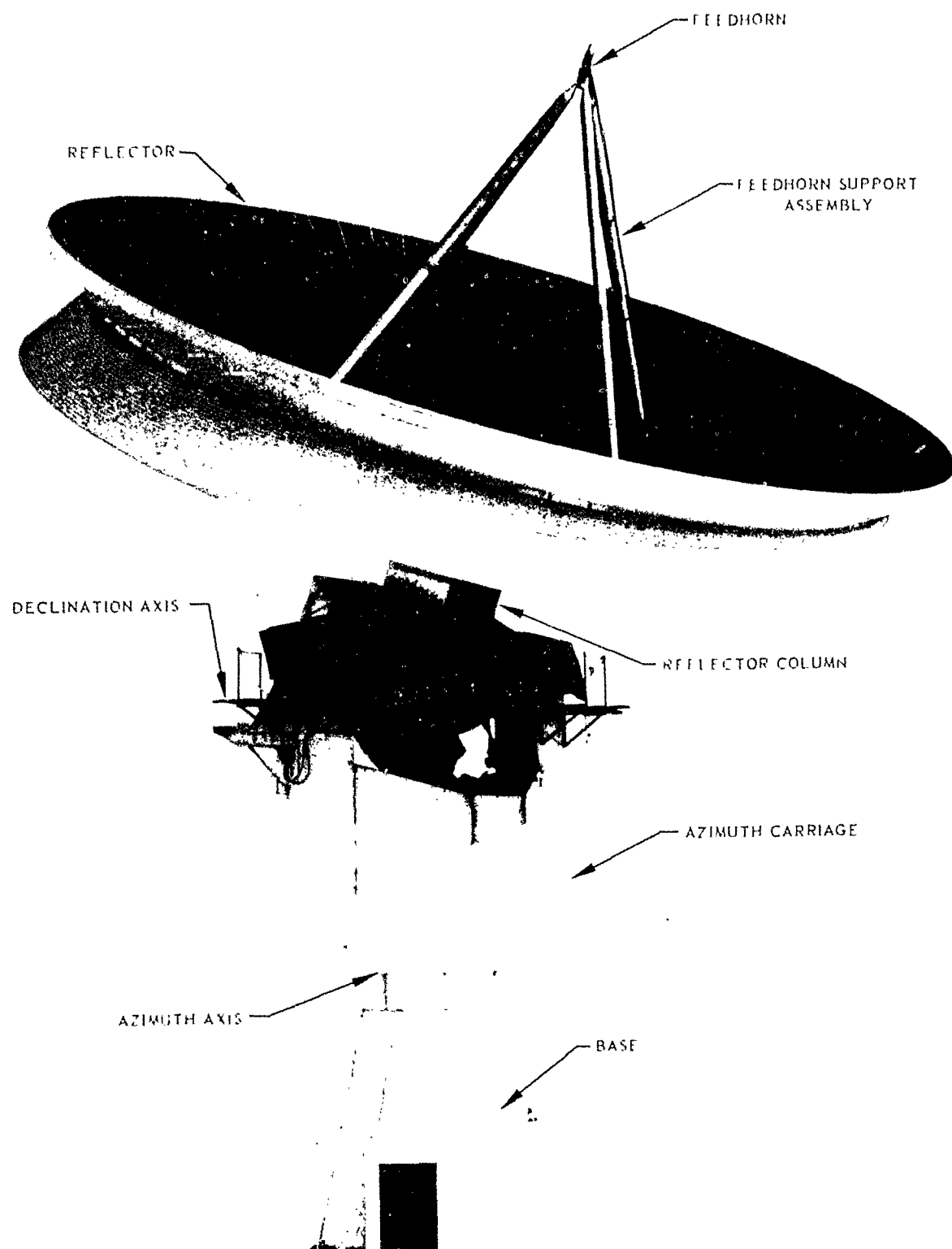
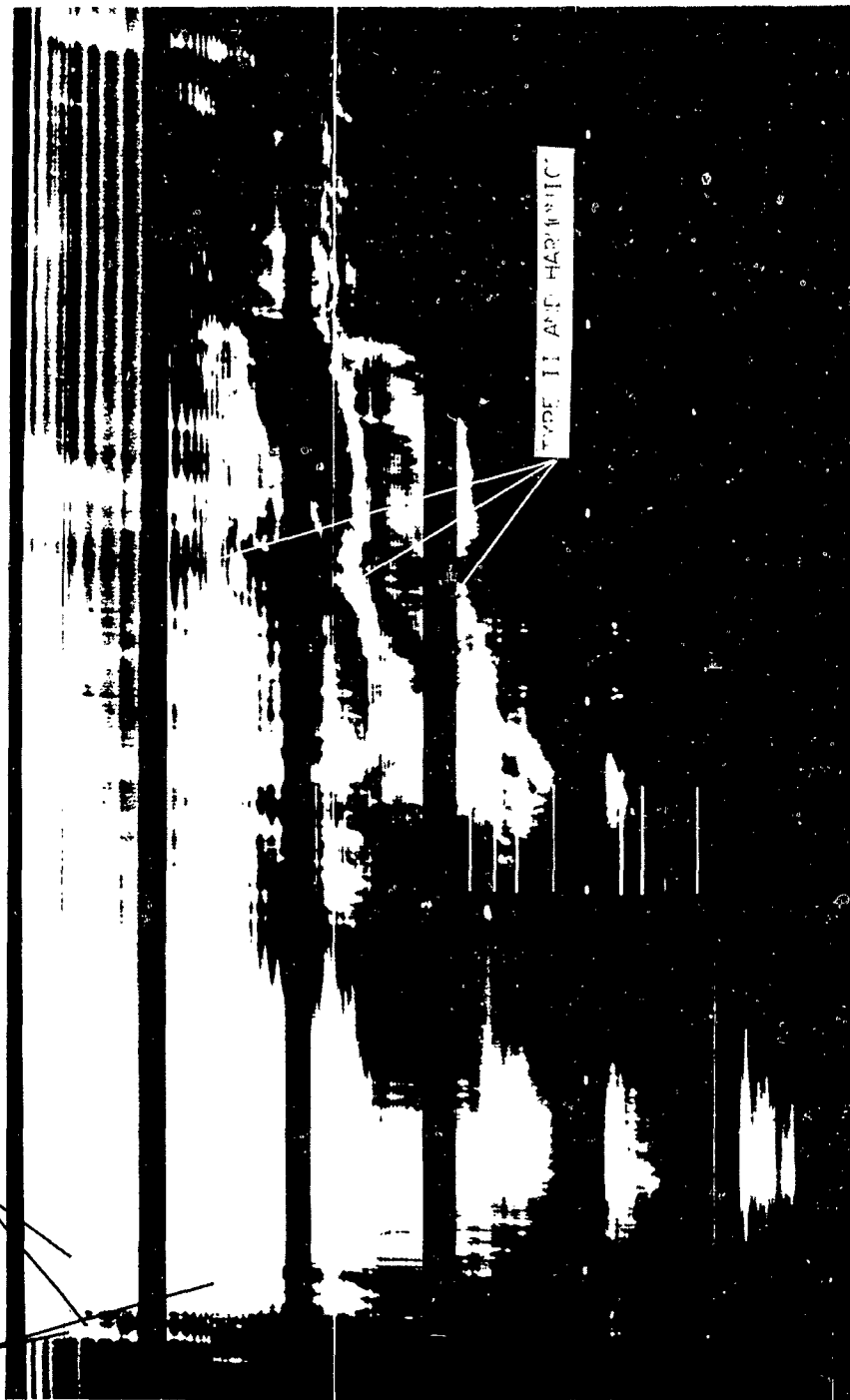


Plate XIX. Example of a radio telescope antenna. (U.S. Air Force)



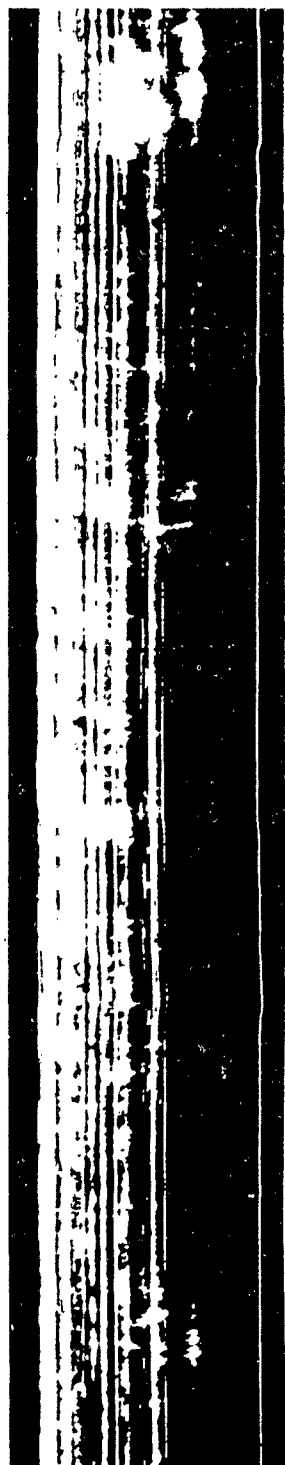
TYPE III TYPE V



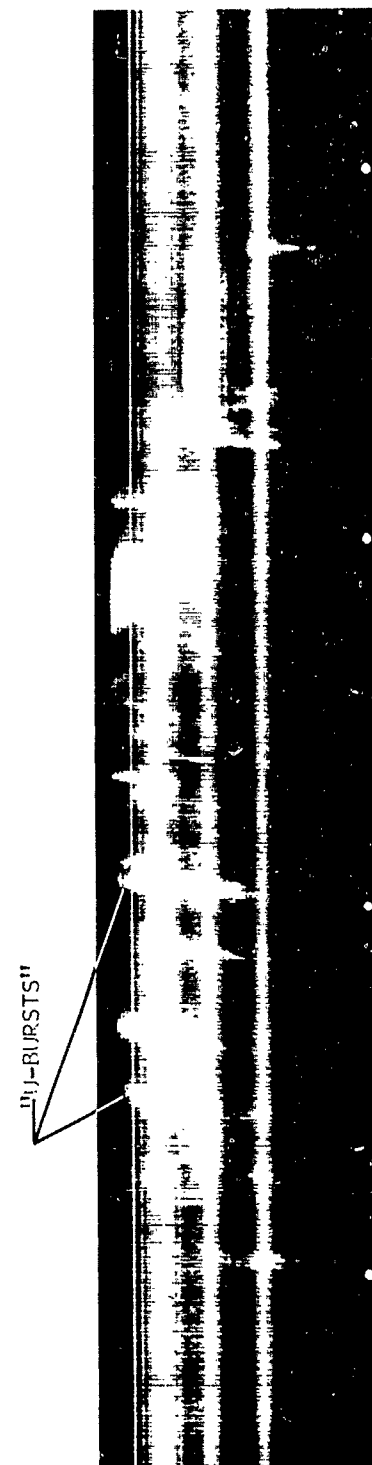
1769 MARCH 10

1724 U.T.

TYPE II, TYPE III, AND TYPE V. (SAC DEAF OES)



1907 U.T. 1959 FEBRUARY 2 1909 U.T.  
TYPE I EMISSIONS



2405 U.T. 1959 APRIL 8 2408 U.T.

PLATE XVI. EXAMPLES OF THE SOLAR RADIO TYPE I AND "UJ-BURST" EMISSIONS

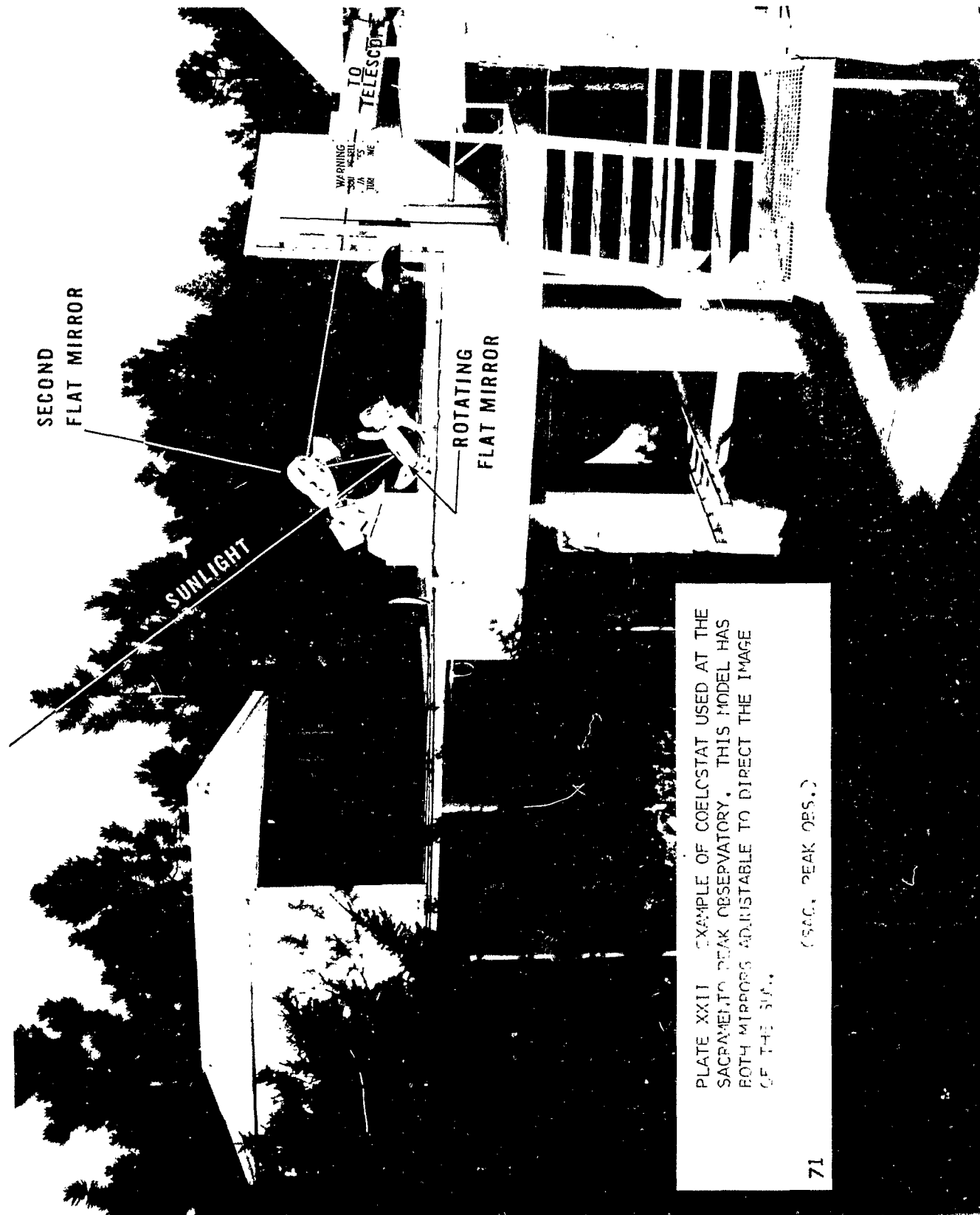
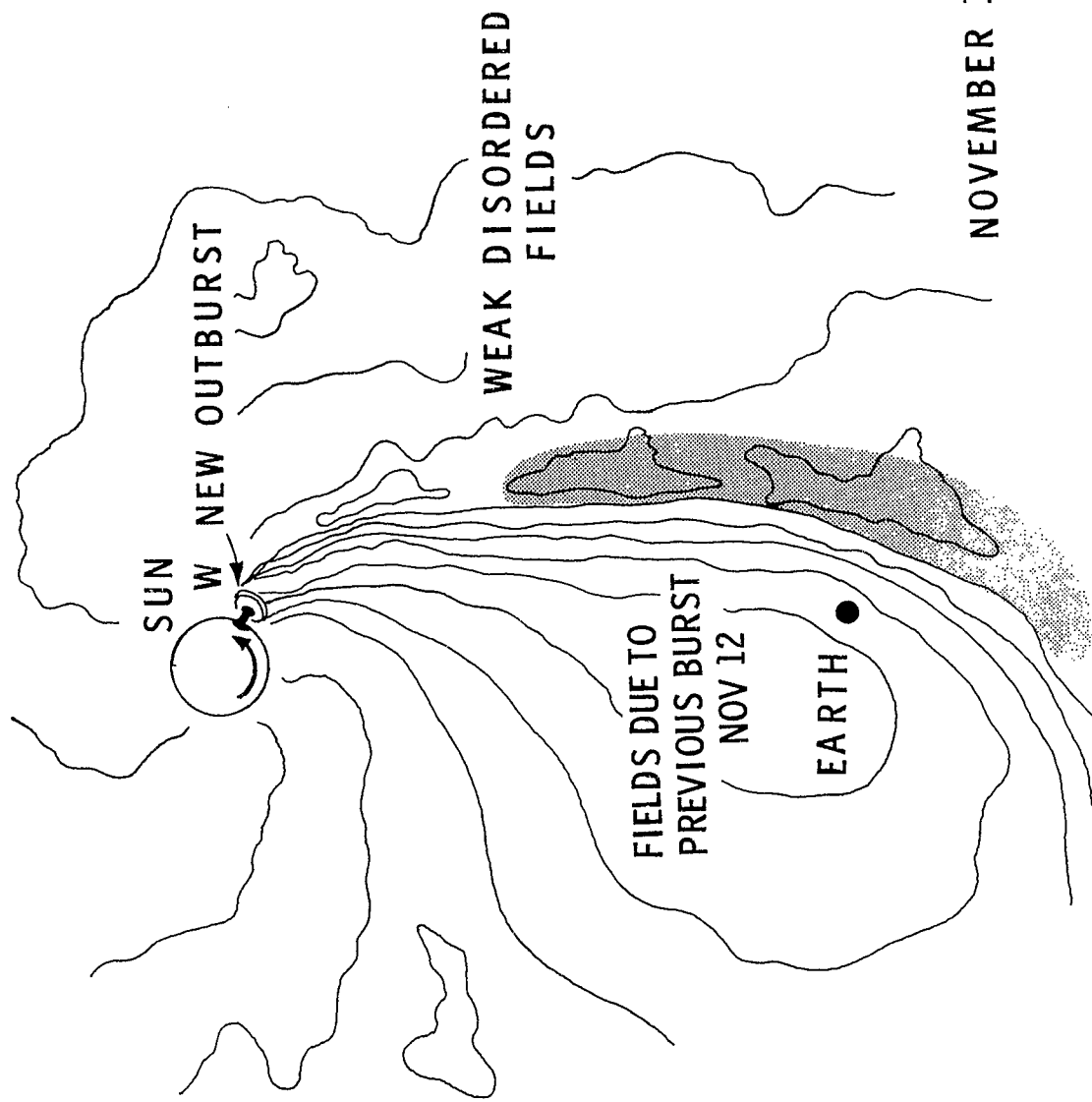


PLATE XXII EXAMPLE OF COELOSTAT USED AT THE SACRAMENTO PEAK OBSERVATORY. THIS MODEL HAS BOTH MIRRORS ADJUSTABLE TO DIRECT THE IMAGE OF THE SUN.

(SAC. PEAK OBS.)



NOVEMBER 15, 1960

FIGURE 12. SCHEMATIC DIAGRAM OF THE MAGNETIC FIELDS IN THE INNER SOLAR SYSTEM AT 0230 UT ON NOVEMBER 15. THE EARTH IS NOW INSIDE A MAGNETIC BOTTLE FORMED BY LOOPS OF FORCE ATTACHED TO THE SUN. THE SHADED AREA REPRESENTS REGIONS OF CHAOTIC FIELDS.

smooth and constant and the charged particles propagate along an organized spiral path. In complex, rapidly changing fields, particle motion is a diffusion-like process in which particles are scattered by regions of high field intensity, and travel in straight lines in regions of low intensity [9]. The diffusion process may explain the slowly decaying isotropic flow of particles. Table 7 briefly summarizes this section.

Table 7. Solar Flare Particle Radiation

<u>Radiation</u>	<u>Flux</u>	<u>Particle Energy</u>
Proton	<u>(Particles/cm<sup>2</sup>/sec)</u>	
Relativistic	Usual 10 to 10 <sup>2</sup> Occasional 10 <sup>4</sup>	1 to 10 Bev*
Non-relativistic	Usual 10 <sup>4</sup>	30 to 300 Mev
Electrons at mag lat 76°	Probable 10 <sup>4</sup>	100 Mev
X-rays and gamma rays	<u>Energy flux (ergs/cm<sup>2</sup>/sec)</u> 10 <sup>-2</sup> to 10 <sup>-5</sup>	

#### c. Galactic and Extragalactic cosmic rays

The sun contributes only 10<sup>-9</sup> of the general cosmic radiation of our galaxy. Galactic and extragalactic protons reaching the earth have energies in the range from a few Bev to greater than 10<sup>10</sup> Bev and arrive with nearly uniform intensity from all directions (isotropic) [35a]. While it is highly unlikely that the total production of these cosmic rays is affected by events in the solar system, both the number and energies of galactic particles observed near the earth are closely related to the solar cycle. The relationship is summarized by H.V. Neher [53]:

"1. There is a large change during a solar cycle in the cosmic ray particles reaching the vicinity of the earth. The total energy changes by some 40 percent and the total number of particles down to proton energies of 100 to 150 Mev changes by a factor of 4 or 5."

"2. There is nearly an inverse relationship between general solar activity and cosmic ray intensity."

\*More recent observations give values to 30 Bev as noted earlier.

"3. The lower energy particles are affected more than those of high energy. It appears that few, if any, primary protons below 600 to 700 Mev are present in the vicinity of the earth during solar maximum."

"4. Throughout most of the solar cycle there exists a knee\* in the latitude curve at high latitudes. Its location moves only slightly with the solar cycle, being at about  $55^{\circ}$  during a solar maximum and about  $57^{\circ}$  during a solar minimum."

"5. Cosmic ray intensity is not exactly anticorrelated with general solar activity as measured by Zurich sunspot numbers by 6 to 12 months. We interpret this to mean that this represents the time for the accumulation of solar matter that is responsible for modulation, i.e., turning away cosmic rays."

#### (1) The Forbush decrease

Within 24 to 40 hours after a large solar flare, galactic cosmic ray intensity sometimes decreases to a minimum of about 10 percent below its original value. Such drops occur almost simultaneously with magnetic storms, auroras and other solar effects [66]. Recovery to the preflare value is gradual with a half life of 1 to 2 days and sometimes longer. The decrease is coincident with a greatly increased flux of solar protons (see Figure 10). Apparently, the magnetic tongue (Section 4) produced by a flare provides an efficient path for solar particles, but the concentration of lines of force around its periphery is sufficient to deflect the lower energy galactic particles and prevent them from reaching the earth. The varying delay times may be explained by varying configurations of the solar field. Pioneer V observations have established the fact that whatever mechanism is responsible for the Forbush decrease it operates over a large spatial volume and is not restricted to the vicinity of the earth [51].

#### (2) Variation with solar cycle

During the period of the solar cycle, galactic and extragalactic cosmic ray activity decreases while solar activity increases, with a lag of 9 to 12 months and an amplitude of about 40 percent

\*If the ionization observed in ion chambers is plotted against geomagnetic latitude for a given atmospheric depth, a sharp break occurs at about  $50^{\circ}$  to  $60^{\circ}$  with decreasing ionization toward the equator. This discontinuity is the "knee".

near the earth. The flux of primary protons with energy greater than 150 Mev decreases by a factor of 2.4 from solar minimum to solar maximum.

### (3) 27-day cycle

Cosmic ray flux has a 27-day cycle of about five percent amplitude at sea level, apparently related to the rotation of active centers on the solar disk.

### (4) Diurnal

There are recurring 24-hour variations produced by relativistic effects of the interaction of the cosmic-rays with the interplanetary magnetic field originally produced on the sun. The amplitude and direction of maximum cosmic-ray intensity varies with the solar wind velocity. Thus the diurnal variations vary as the solar wind and may allow estimates of the solar wind velocity by measurements of the diurnal variations. [26] .

### d. Showers

Primary particles from solar, galactic and extragalactic sources have a predominant positive charge when they reach the atmosphere. About 85 percent of the primaries are protons, 14 percent helium nuclei (alpha particles), and one percent nuclei of other heavier elements [17] . Outside the atmosphere, primary particles follow the earth's magnetic lines of force, while within the atmosphere they follow straight lines. Secondary radiation is produced as the primaries strike the atmosphere between 15 and 35 km. The secondaries consist of all kinds of elementary particles, some heavy nuclei, and electromagnetic radiation, but the ratio in which various types occur depends on the energy of the primaries. For low energy primaries there are more neutrons than charged particles. In a solar flare cosmic ray event, mesons may be increased by 20% and neutrons by 400% at sea level. High-energy secondaries interact to produce proton showers as shown schematically in Figure 13. Normal duration of a shower is 3 or 4 days. Thirty-five occurred from 1956 through mid-1961, following the onset of large flares by 30 minutes to five hours. About 25% of 3 and 3+ flares and a much smaller percentage of 2+ flares produce showers. As yet there is no method of anticipating whether a flare will produce a proton shower, but because showers occur only with flares, the probability of encountering a shower is reduced by a factor of 10 or more when known solar flare indicators are absent.

### e. Geomagnetic influences

Material in this section presupposes some background of information such as in Chapter X, the Handbook of Geophysics, 1959 edition. Some of

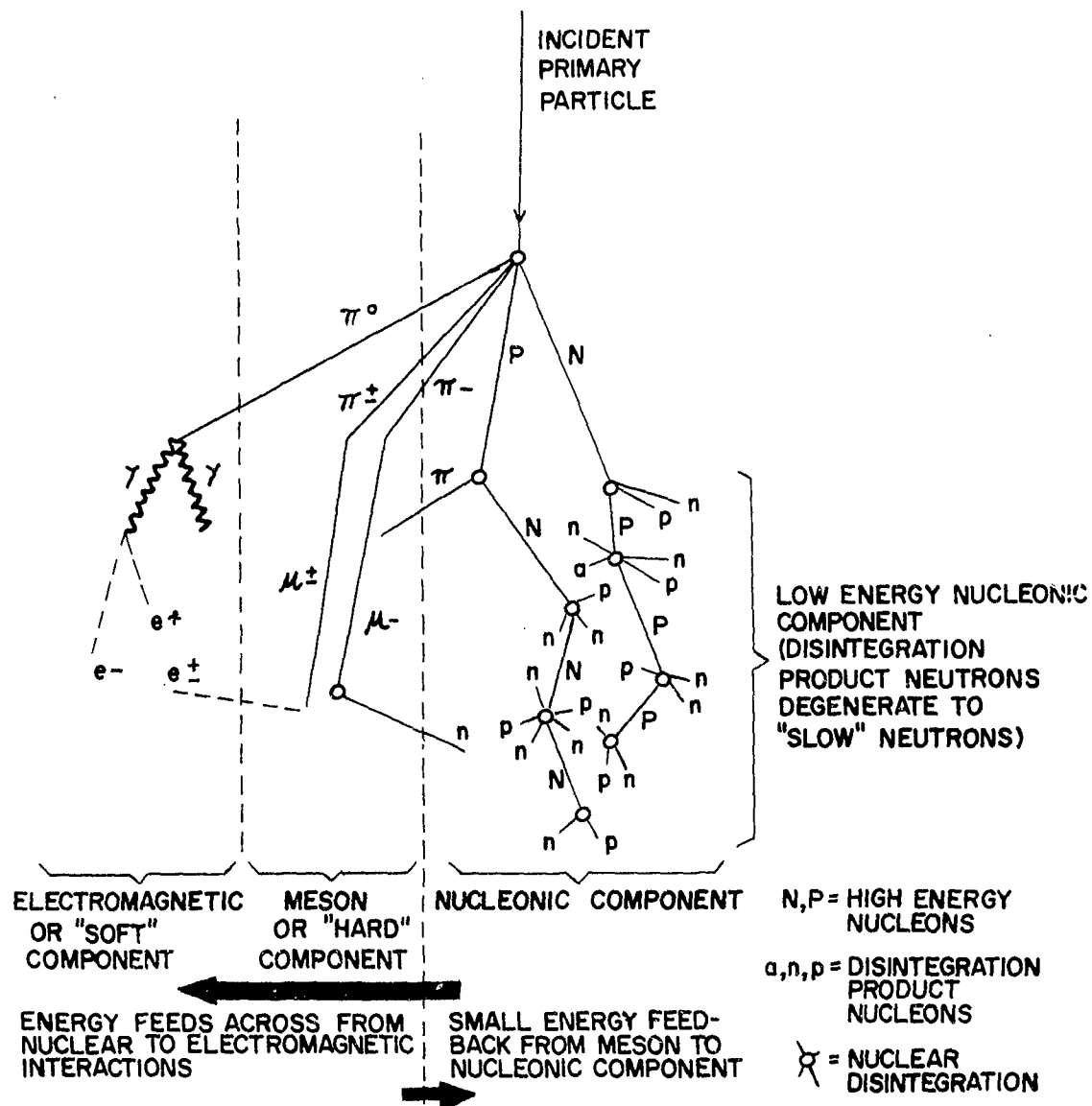


FIGURE 13. THE DEVELOPMENT OF SECONDARY COMPONENTS OF THE COSMIC RADIATION IN THE ATMOSPHERE FROM PRIMARY COSMIC RAY PARTICLES. (FROM J. A. SIMPSON, ASTROPHYSICAL JOURNAL SUPP. 4, 379, 1960, UNIV. OF CHICAGO PRESS.)



this material is repeated here for continuity of discussion.

### (1) Main Field

The main field of the earth is that of a magnetic dipole, and arises from the molten core which comprises the inner half of the earth's diameter. Superimposed on the main field are internally-produced regional anomalies which cover several hundred thousand square miles and are due to currents within the earth, and smaller surface anomalies due to local iron deposits. The earth's field extends to about 10 earth radii on the sunward side of the earth and has been characterized as ending at the boundary between our atmosphere and the solar corona [11]. In recent years, data from earth satellites with highly eccentric orbits (Pioneers III and IV and Explorers VI, X, XII and XIV, etc) have shown the magnetospheric boundary to "flare" outward on the side of earth away from the sun. Between this boundary and the shock fronts formed by the interaction of the solar wind and the magnetosphere (thickness  $\approx 3R_e$ ) is a transition zone [30]. A recent discussion of the magnetosphere can be found in [22a].

### (2) Time variations

There are also externally-produced variations with time, caused by the cloud of low-energy particles emitted from an active sunspot region, and by the shock wave at the leading edge of the cloud. The main field undergoes a gradual secular change of 0.1% per year, and regular diurnal changes. In addition, large irregular time variations occur over periods ranging from seconds to days, with amplitudes ranging from order  $10^{-2}$  to  $10^2$  gammas\*.

Time variations occur in several groups as follows, beginning with the shortest period: (1) micropulsations lasting 10 minutes to an hour; includes crochets, (2) disturbances lasting two to three hours, (3) systematic diurnal variation, (4) geomagnetic storms lasting several days; sudden and gradual commencement types, (5) approximate 27-day variation in micropulsations and disturbances, (6) seasonal variation with maxima at the equinoxes, (7) solar cycle variations of disturbances and geomagnetic storms, (8) gradual secular change of 0.1% per year.

\*one gamma =  $10^{-5}$  oerstead; 1 oerstead = the magnetic field produced at the center of a plane circular coil of one turn, with radius one cm, which carries a current of  $(2\pi)^{-1}$  abamperes. one gamma =  $10^{-5}$  gauss in space if the free space permeability equals one.

Time variations in intensity or direction of field affect magnetic compass navigation and radio propagation. These effects are most pronounced in the auroral zones (latitude  $67.5 \pm 5^\circ$ ).

Geomagnetic variations are measured by F, the intensity of the total field, or by the components D, H, Z, or X, Y, Z, or D, H, I, where:

D = declination or magnetic variation, the angle between the horizontal component and geographic north, positive toward east.

H = horizontal component

Z = vertical component

I = inclination (dip), the angle between vectors F and H, positive downward.

X = horizontal northerly component

Y = horizontal easterly component

#### (a) Micropulsations

Geomagnetic micropulsations are regular, wavelike oscillations of the earth's field. The Pc type has periods of 1-30 seconds, amplitude of 0.1 gamma, and may last several hours and which usually occurs during day-light hours. The Pt type has a longer period and large amplitude, but lasts only about 10 minutes and occurs at night. Micropulsations with amplitudes up to 40 gammas occur in the auroral zones. Their frequency reaches seasonal maxima at the equinoxes, and has a 27-day periodicity coincident with solar rotation [19]. They are related to the arrival of solar particles, but not necessarily to their energy or density. Worldwide micropulsations "storms" occur at times of major geophysical disturbances. Their occurrence follows the appearance of unipolar magnetic regions on the sun. They are associated with the intensity of auroras at both high and low latitudes, but increase in amplitude at time of great ionospheric absorption of cosmic noise. There is a daily local time variation of pulsation amplitude. The amplitude seems related to the energy and density of charged particles in the local ionosphere. The micropulsations of the field at ionospheric height could periodically supply enough additional energy to incoming particles to raise the particles to the level required for the excitation of the aurora. The added energy, in conjunction with enhanced particle density, would increase the collision frequency,

which would give rise to greater ionospheric absorption of cosmic noise.

A magnetic crochet is a micropulsation which occurs on the daylight side of the earth immediately after, or within a few minutes of, some large flares. A crochet is a positive pulse in the H component lasting 10 minutes to an hour, and is due to enhanced X-ray and ultraviolet radiation from the parent flare [4]. Crochets are observed only during Importance 3 or 3+ flares, and last only for the duration of the visible H- $\alpha$  flare or less. They lag only  $2\frac{1}{2}$  minutes behind H- $\alpha$  maximum, while most SID's lag 5 minutes or more [32].

#### b. Disturbances

Geomagnetic disturbances are distinguished from micropulsations by having a minimum amplitude of 150 gammas, and durations of two to three hours. There is a tendency for disturbances to have a recurrence interval of about 27 days (probably 24 to 29), coincident with the rotation of active regions on the sun. However, this fact has little prediction value because active areas do not produce the same effect on each rotation. There is also a semi-annual variation with maxima at the equinoxes, when the earth lies in a position favorable for direct radial emission of particles from the sun. Disturbance activity follows the 11-year solar cycle, but usually has a lag of about a year. A magnetically active or disturbed day has several large variations lasting 3 hours or less; a quiet day has little or no variation from the smooth diurnal curve.

#### c. Diurnal variation

The solar wind, flowing past the earth at supersonic speed, compresses the magnetosphere on the upstream, or lighted, side of the earth, and draws it out in a long tail on the downstream side. Thus the field has the aspect of a teardrop, which continually presents its blunt end to the sun as the earth rotates beneath it. A standing, collision-free, magnetohydrodynamic shock wave is created in the solar wind on the upstream side of the earth by the geomagnetic field [22a]. Interrelated with the solar wind effect are the effects of solar heating, and ionization of atmospheric constituents during daylight.

#### d. Geomagnetic storms

Storms are intervals of pronounced magnetic activity with rapid chaotic fluctuations of magnetic indices over the entire earth. The principal feature is a marked decrease in H, which

reaches a minimum point within a few hours and gradually returns to normal after several days. This trend is best shown by the mean values for 6 hours or more, which smooth the short-period variations. During "great" magnetic storms the variations are about 5% of total field strength at high latitudes and 2% at low latitudes. Great storms occur about once a year on the average, and much more severe storms occur once in several years. Variations about 1/10 as large as those of major storms occur several times a month. About 75% of the variation is due to sources outside the earth, mainly in the ionosphere. Geomagnetic storms are of two types: (1) SC (sudden commencement) storms, which are intense, nonrecurrent, and associated with flares, (2) GC (gradual commencement) storms, which are recurrent and are associated with M regions\*.

Storms are produced by corpuscular radiation, and are generally related to flares which appear near the central meridian of the sun; only occasionally are they produced by flares near the limb.

#### 8. ~~27-day~~ period

Micropulsations and disturbances have an approximate 27-day variation because they are produced by particles emitted from active regions which rotate with the sun. When these particle producing regions pass the central meridian, geomagnetic activity reaches a peak two or three days later.

#### (3) Interrelations of geomagnetic and other solar-related phenomena

(a) Geomagnetic storms are more frequent than PCA events, but almost all PCA's are followed after a day or two by a strong magnetic disturbance.

(b) Forbush decrease of galactic cosmic rays (see Section 6b) occurs near the beginning of a magnetic storm.

(c) With increasing geomagnetic activity there is a shift in maximum auroral activity toward the equator, producing a high frequency of auroras below 68° magnetic latitude but little change within the auroral zone.

\*M regions are large areas of the sun which continue to emit streams of plasma for long periods; named by J. Bartels. Very little is known about these regions which seem to rotate with the sun (similar to R regions - See Section 5.b.(3)(e)).

(d) The Zurich sunspot numbers have a small peak at a periodicity of about 25 months. This is reflected in a biennial variation of the amplitude of geomagnetic indices amounting to 8 gamma in Z, and 1 minute of arc in D. In H and X, the curves of this variation are similar for different stations. The character of the D and Y variations are dependent on the magnitude of D. Sunspot number and geomagnetic activity are closely related on an annual basis, with the maximum in geomagnetic activity lagging behind the solar maximum by about a year or two.

#### (4) Indices

The amplitude of variations in the earth's field is dependent on latitude and local time, in addition to the effects discussed above. The commonly used indices are given below [13]:

K - Equivalent 3-hour range of the component having the largest variation, ranging from 1 to 9 on a quasi-logarithmic scale ( $a_p$  in linear scale).

$A_k$  - Equivalent daily amplitude, averaged over 8 observations of  $a_k$  per day, where  $a_k$  is a 3-hour measure, in 2 gammas, of the scaled amplitude of the largest variation (it is related to K but differs for each measuring station whereas the K's may be the same).

$K_p$  - Equivalent planetary amplitude; average of K at 12 stations. ( $A_p$  in linear scale).

#### f. Ionosphere

##### (1) Structure

The earth's ionosphere is a thick layer wherein large numbers of positive ions and negative electrons are imbedded in a neutral gas. It is subdivided into the D, E, and F layers at the approximate elevations 50 to 90 km, 90 to 160 km, and 160 to about 300 km, respectively. In daylight the F layer is separated into F1 from 160 to 210 km and F2 from 300 to 500 km. During the day electron density is about  $1.5 \times 10^5$  electrons/cm<sup>3</sup> in the E layer and  $2.5 \times 10^5$  to  $1 \times 10^6$  electrons/cm<sup>3</sup> in the F layer [47]. The ionosphere is maintained principally by ultraviolet and X-ray radiation of wavelengths from about 1 to 1300 A acting on molecular and atomic oxygen and nitrogen, and the trace constituent nitric oxide. The two most important contributions of photospheric radiation are the dissociation of molecular oxygen in the Schumann

continuum, 1350 to 1750 Å, and the photo-detachment of electrons from negative ions by the entire spectrum below the visible yellow [32].

Lyman- $\alpha$  (1215.7 Å) is the most important feature of the solar ultraviolet spectrum down to 977 Å. During quiet sun periods rocket measurements rarely show any X-ray penetration below 100 km. The only ionizing radiation penetrating the D region at such times is Lyman- $\alpha$  which ionizes the trace element nitric oxide. Solar flares produce greatly enhanced X-radiation, which increases the ionization of the D layer. This causes the D region to absorb all radio reception (SWF). Fade-out occurs over the entire lighted hemisphere and may last several hours. X-rays are several thousand times as efficient as Lyman- $\alpha$  in ionizing all elements of the D region.

Radiation entering the atmosphere is diminished by absorption until, at some specific altitude, a maximum rate of ion production occurs. Ion density decays at night at a rate depending on the recombination coefficient. The probable major process of ion destruction is recombination.

Before proceeding with the discussion it is necessary to define some terms. The critical frequency,  $f_o$ , of a given layer is the frequency at which reflection of vertically-directed electromagnetic radiations just begin to disappear, and the radiation begins to be refracted upward and transmitted through the layer; or it is the frequency at which backward scatter begins to be replaced by forward scatter. The electron density, or number of electrons per unit volume,  $N_e$ , is related to critical frequency by

$$N_e = 1.24 \times 10^4 f_o^2 \quad [4]$$

The critical frequency is shown by a point of inflection on an ionogram, which is a curve relating frequency and equivalent height. The equivalent height,  $K$ , is the height from which an electromagnetic wave front would have been reflected if it had traveled all the way with free space velocity. The equivalent height depends on group velocity, and therefore on electron density at all heights. The layers of the ionosphere are not necessarily formed of high concentrations of electrons. They are properly defined by the electron profile,  $N_e(h)$ , which is a curve of electron density vs geometric height,  $h$ . The  $N_e(h)$  curve has inflections at heights corresponding to the critical frequencies  $f_oE$  and  $f_oF1$ , and peak at  $f_oF2$  [32].

## (2) Sudden ionospheric disturbance (SID)

Flares are often followed immediately by increases in ultra-violet and X-ray emission, which quickly produce increased ionization in the 60- to 100-km region of the ionosphere on the lighted side of the earth. The effect is most noticeable in the D region. Return to normal requires about 20 to 90 minutes. The larger disturbances of this kind are sometimes accompanied by a magnetic crochet (Section 6.d.(2)(a)). There is a corresponding increase of about 10% in the critical frequency of the E layer,  $f_oE$ , and sometimes of  $f_oF$ . The following additional phenomena are associated with SID, and are due to increased ionization of the D and E regions [32]:

(a) Waves traversing the D and lower E regions

1. SCNA. Sudden Cosmic Noise Absorption; a decrease in strength of radio waves arriving from cosmic sources.
2. SWF. Short Wave Fadeout; a decrease in strength of short radio waves reflected either vertically or obliquely from the E or F layer in the band 5 to 20 Mc/sec. "Polar blackout", in which radio signals disappear completely in the polar regions, is most frequent at night.
3. A change of phase of waves reflected at nearly vertical incidence from the E or F layers.
4. A change of group path of waves reflected at nearly vertical incidence from the E or F layers.

(b) Waves reflected in the D and lower E regions

1. A decrease in strength of wave of frequencies below 300 Kc/sec reflected at oblique incidence.
2. An increase in the strength of the waves of the same frequencies reflected at vertical incidence.
3. SEA. Sudden Enhancement of Atmospherics; an increase in the strength of very-low-frequency atmospherics, particularly near 22 Kc/sec. The increased signal strength results from reflectivity of the D region at oblique incidence.
4. SPA. Sudden Phase Anomaly; a decrease in the phase lag of frequencies less than 300 Kc/sec. SPA is caused by the reflection of very long radio waves from a lowered ionospheric ceiling at the base of the D region. The logarithm of the reflection coefficient (  $\rho$  ) increases with sunspot number (R). This increase

is greater in summer than in winter. The mean change in reflecting height is about 4 km for most flares. This is the difference in penetration of the atmosphere by Lyman- $\alpha$  and X-rays down to wavelength 1 A. X-rays shorter than 6 A are rarely observed at quiet sun, but rocket measurements have detected wavelengths as short as 2 A in great abundance during flares [54, 59].

5. An increase in the strength of waves of about 40 Mc/sec received by forward scatter from the D region.

6. Appearance of weak reflections from levels near 60 km of vertical incidence waves at 1 Mc/sec.

7. Change in the intensity of thermal radio-frequency radiation from the ionosphere.

At low latitudes the decreased amplitude of radio signals is not observed, but the main phase of a magnetic storm is often accompanied by a rapid variation in amplitude of low-frequency waves (30 to 3000 Kc/sec) and the phase of very-low-frequency waves (less than 30 Kc/sec). In intense storms there may be an after effect of unusual variation from the mean diurnal phase height curve, which begins a day later and lasts several days.

### (3) Ionospheric storms

If the stream of charged particles emitted by a flare is to intercept the earth, it does so in 24 to 36 hours, producing an ionospheric storm, and sometimes auroras and a magnetic storm. Sunspot activity, ionospheric storms, geomagnetic storms, and auroras are highly correlated for major events, but the correlation diminishes for lesser disturbances. An ionospheric storm is a phenomenon of the F region, occurs all around the earth, and can last several hours or days. It is characterized by a marked decrease (negative phase) or increase (positive phase) of the critical frequency of the F2 layer,  $f_oF2$ . In middle latitudes the negative phase is most pronounced, but is usually preceded by a brief positive phase. At lower latitudes the positive phase is dominant.

### (4) Correlation with solar variations

#### (a) D Region

The  $|\log r|$  increases with sunspot number, where  $r$  is the reflection coefficient of the D region. The increase is larger in summer than in winter.



## (b) E and F Regions

1. In general, the effect of sudden enhanced solar ionizing radiation is to increase the height and decrease the critical frequency of the F region. The effect varies with geographic location and local time as mentioned above.

2. The monthly mean of  $f_oE$  closely follows sunspot number.  $f_oE$  also has a 28-day variation in phase with the 10.7cm radio flux.

3. Sunspot number varies as the 4th power of critical frequency, or the square of electron density of the E and F regions, but as the square of  $f_oF2$ , or directly as the electron density in this highest region[19].

4. The critical frequency  $f_oF2$  varies markedly with the solar cycle, and is highest at sunspot maximum. World-wide results are described by

$$(f_oF2)^2 \propto (1 + 0.02\bar{R})$$

where  $\bar{R}$  is the mean Zurich sunspot number. Electron density of F2 is also closely related to  $R$ . In the polar regions the variation is different at different places, hours, and seasons. Large day-to-day fluctuations of  $f_oF2$  can be related to the number of plagues on the sun.

5. The equivalent height ( $h'$ ) of the F2 layer increases markedly during an ionospheric storm; the geometric height of F2 also increases, but to a lesser degree[16].

## g. Aurora

The aurora is attributed to streams of relatively low energy charged particles, protons, and electrons, emitted from active regions of the sun or released from the Van Allen belts. If the magnetic configuration between the area of ejection and the earth is suitable, the particles reach the vicinity of the earth in 15 to 30 hours and are deflected by the earth's field toward the auroral zones. The particles spiral down the lines of force and penetrate to various depths depending on their energies. Protons of 0.5 Mev penetrate to 100 Km, which is the average base of auroral arcs; electrons of 10 to 100 Kev would penetrate to 90 to 110 km. The normal elevation range of auroral displays is 80 to 120 km. The charged particles produce ionization of gases in the upper atmosphere, where the recombination of ions and electrons emits light containing the characteristic lines and bands of oxygen and nitrogen.

The green and red colors of the aurora are produced by the excitation of atomic oxygen at wavelengths of 5577 Å and 6363 Å respectively, and the violet, at a wavelength of 3466 Å, by molecular nitrogen. Bursts of X-rays with energies of 100 Kev accompany the formation or brightening of auroral rays [4, 21, 32] .

Zones of maximum auroral occurrence are located somewhat symmetrically about 67° 30' magnetic latitude, but these zones shift toward the poles at sunspot minimum and toward the equator at sunspot maximum. Seasonal maxima also occur and there is a tendency toward an approximate 27-day cycle. A diurnal maximum occurs about 2300 LST [4] . Sub-audio frequency observations of the earth's field show promise of providing a method of predicting auroral disturbances a few hours in advance.

An increase in H, the horizontal component of the earth's magnetic field is followed by the appearance of a red auroral arc, with intense hydrogen emission which stretches longitudinally across the sky. As the night progresses, the arc breaks up to form rays aligned with the magnetic lines of force. This, accompanied by a decrease in the relative intensity of the hydrogen emission line, is used to deduce the velocities of incoming solar protons [19, 29].

Auroral activity seriously affects standard broadcast radio propagation at middle and high frequencies, and in the auroral zones complete radio blackout sometimes persists for several days---mainly at night. The effect is reduced at low frequencies and latitudes.

The aurora usually consists of faint, diffuse, quiet arcs extending over the whole dark side of the auroral zone. Breakup, which is the most violent auroral phenomenon, occurs with the onset of a polar magnetic substorm. It entails sudden and intense increases in brightness and motion. The brightness of all the arcs or bands increases over a large area on the morning side of the earth, together with general north or south movement, and rapid, wavy motions of the arc. Arcs or bands may disrupt into patches. In violent breakup, auroras on the evening side are also disrupted [14] .

Only a brief discussion of the aurora can be included here since it is a complete subject in itself. Much has been written describing the morphology of the aurora and the theories behind the various forms. For more complete information on the aurora, the reader is directed to the various books on the subject, e.g. [2, 23] .

## h. Man-in-Space

According to the National Committee on Radiation Protection, maximum allowable dose rates for humans is 0.23 rem\* per week over a 13-week period, or 0.1 rem per week over a year. The estimated total lethal dose is about 400 roentgen. Natural background radiation at sea level is only 0.003, 25% of which is cosmic; on a 1000 foot mountain, background is 0.04, 50% of which is cosmic. At the top of the atmosphere, the average value is 0.08 and at three earth radii, 0.17. This is due mainly to protons and alpha particles trapped in the Van Allen belts, and only an insignificant proportion to galactic cosmic radiation.

Radiation of the Van Allen belts can be avoided if exit is made above the polar regions. In low latitudes there is a "safe corridor" for orbital flights below 400 km, where Van Allen radiation intensity is low, and where the earth's magnetic field provides reasonable protection against solar sub-cosmic radiation. Solar cosmic ray particles are more dangerous than those of the Van Allen belts because of their very high energy, and because they can probably not be avoided. For this reason, solar cosmic ray events place a serious constraint upon space travel.

With 8 gm/cm<sup>2</sup> of shielding, a man would receive an integrated dose of from 2 to 170 roentgen during a cosmic ray event. Assuming a permissible dose of 25 r. and the above shielding, about 1/3 of the 25 cosmic ray flares which occurred during the 1957-58 maximum period would have exceeded the permissible limit. Due to uncertainties of the radiation intensity, it has been generally accepted that 10 gm/cm<sup>2</sup> is the minimum shielding required [17, 31].

During solar minimum large flares are infrequent, and with careful monitoring of solar indices, space travel would be fairly safe over periods of at least several days and possibly a few weeks. Even during solar maximum, there are periods during which no large flares occur and which would be safe for space travel; however, one or more of the indices are present continually during the maximum phase, and absolutely safe periods cannot accurately be predicted at present. At a sacrifice of approximately 50 percent of the available time, it should be possible, with a refinement of present "solar weather prediction" techniques, to decrease the

\*Rem - Roentgen equivalent, mammal; the dose of any ionizing radiation that will produce the same biological effect (damage) as that produced by one roentgen of high-voltage X-radiation.

chance of an encounter with a large event by a factor of about 10 for a predicting period of about 2 weeks. This should reduce the possibility of a large flare encounter to about one percent for a 2 week voyage [31].

Shielding offers protection against primary particles but may be ultimately harmful because of secondary radiation produced in the shield itself. The first 100 gm/cm<sup>2</sup> of shielding actually increases the hazard from very high energy particles, because of proton showers which occur in the shielding material [17];

#### i. Temperature-Density

##### (1) Temperature

During periods of high solar activity, greatly increased amounts of ultra-violet, X-ray, and corpuscular radiation reach the earth's atmosphere. This energy is absorbed by oxygen and ozone in the outer atmosphere and increases the temperature [20]. The major source of heating in this region is extreme ultra-violet (EUV) radiation (220-900 Å) which has its principal effect in the altitude range 150 to 250 km. In the layer 100 to 280 km, the main atmospheric constituents are molecular and atomic oxygen and nitrogen. Most of the energy of the ultra-violet is carried in a few strong lines, such as Lyman- $\alpha$  (1216 Å) and He II (304 Å). Since most of the Lyman- $\alpha$  is absorbed below 100 km, the 304 Å line of ionized helium is probably the most important for heating between 100 and 280 km. Corpuscular radiation is estimated to account for 10% of the heating in this layer. Warming causes an outward expansion of the atmosphere, and increases the density at elevations above 200 km. The maximum day-time temperature in the exosphere is about 35% higher than the minimum night-time temperature. The temperature increase varies directly with sunspot number, R, and for given R is greater in summer, at low latitudes, and at high elevations.

Temperature changes due to ultraviolet radiation are related to the solar power flux density at 10.7-cm wavelength by

$$\Delta_1 T \approx 2.5^\circ \Delta F$$

where  $\Delta_1 T$  is temperature change in degrees Kelvin and  $\Delta F$  is the change in the solar power flux density in units of 10<sup>-20</sup> watts meters<sup>-2</sup> cps<sup>-1</sup>. Heating by corpuscular radiation is related to 10.7-cm flux by

$$\Delta_2 T \approx 2.0^\circ \Delta F$$

where  $\Delta F$  is the change in the monthly mean of the 10.7-cm flux. Changes in exospheric temperature are related to the geomagnetic index,  $A_p$ , by

$$\Delta T \approx 1.5^\circ \Delta A_p.$$

The constant,  $1.5^\circ$ , is more nearly  $1.0^\circ$  in the lower satellite levels [57].

## (2) Density

Density between 280 and 800 km varies with the amount of solar ultraviolet energy absorbed in the shallower layer 100 to 280 km, and undergoes a large, smooth diurnal variation with a minimum at about 0400 LST and a maximum at about 1400 LST, i.e., the bulge lags 20 to 30 degrees behind the subsolar point [48]. Radio emission in the wavelength range 10 to 20 cm is a fairly good indicator of density changes; 10.7 cm is often used.

In the region 100 to 200 km there is a normal day-to-night decrease of a few percent, but the day-to-night ratio increases rapidly with elevation above 200 km. At 700 km there is a normal day-to-night ratio of 7-to-1 to 13-to-1, depending on solar power flux density. Solar flares have caused density changes of up to 40% at 200 km. Above 700 km the increase of ratio with height levels off, and may even reverse. There is a "27-day period" of density change related to solar rotation, but actually the period varies from 24 to 37 days. The variation in period apparently occurs because active regions appear at various solar latitudes which have different rotation rates, and because the active regions change with time. Density has a seasonal variation, with maxima during February-April and October-November, and minima during December-January and June-July. It has no known latitudinal variation. The day-to-night ratio at a given elevation varies inversely with solar activity, as indicated by the 10.7-cm radio flux. Apparently, nighttime density is increased enough during high solar flux to reduce the ratio. The relation of density ( $\rho$ ) to power flux density ( $S$ ) is shown by

$$\rho \propto S^m$$

where  $m$  is a constant derived empirically from satellite observations and is inconsistently larger at night than in the daytime [58].  $S$  is given in units of  $10^{-20}$  watts meters<sup>-2</sup> cps<sup>-1</sup>, as above. The density maxima are centered roughly on the equinoxes, when the earth lies in the path of direct corpuscular radiation from

the sun. The amplitude of seasonal variation increases with elevation and solar flux, and because of the latter, is related to the solar cycle.

Density above 200 km increases during large magnetic storms, probably because of solar corpuscular radiation. Hydromagnetic waves are set up when a stream of particles passes into the earth's magnetic field. Dissipation of these waves, and resultant heating, should occur in the F1 layer. A good correlation has been found between the  $A_p$  magnetic index and density over a wide range of heights, with a constant of proportionality which increases rapidly with height[57].

### (3) Satellite acceleration

Because solar radiation strongly affects density in the high atmosphere, fluctuations in this radiation are highly correlated with changes in the velocity of satellites. Jacchia[41] gives four types: (1) Fluctuations which follow the rhythm of 10.7-cm radiation. These increase in amplitude with height and become smaller or disappear when the perigee is in darkness. They probably reflect variations in density caused by radiation in the extreme ultraviolet. (2) Diurnal variations. These are smooth fluctuations connected with the position of perigee with respect to the subsolar point. They are small at 200 km but become large above 350 km. They are intimately connected with (1) and should have the same origin. They reflect the difference in density profiles of the lighted and dark hemisphere of the earth. (3) Transient fluctuations accompanying magnetic storms. These seem to be caused by heating of the atmosphere through interaction with corpuscular radiation. (4) Erratic fluctuations of unexplained origin.

A close correlation between satellite periods and sunspot numbers was found by Paetzold, who has developed a model for atmospheric variations above 150 km, based on the following effects:

#### (a) Solar wind

1. Solar activity
2. Diurnal

#### (b) Corpuscle

1. Magnetic storm
2. Annual and semi-annual (plasma)

Paetzold has stated that temperature and density are increased by solar storms, independently of magnetic latitude and local time. For Sputnik III,

drag increased by a factor of 1.40 at 165 km due to this effect. The plasma effect is due to an indirect interaction of ionospheric plasma with interplanetary plasma (the solar wind). This effect has a weak dependence on solar activity.

#### j. Weather

##### (1) Clouds

Experimental results indicate that cirrus clouds, and cloudy days, may be more frequent during periods of enhanced solar emission [34].

##### (2) Temperature

It appears that mean air temperature at the earth's surface, at least in the tropics, varies inversely with the solar cycle [1]. Garvin [35] showed that temperatures at 1000, 50, and 30 mb and 1000 and 30 mb heights at San Juan are better related to sunspot number than to the geomagnetic indicator. The relationship is best at low latitudes, in summer, and at high altitudes. Heights at 30 mb have a positive correlation, and heights at 1000 mb a negative correlation, with sunspot number.

##### (3) Climate

There is an 11-year periodicity in the width of the rings of redwood trees, implying a corresponding periodic fluctuation in climate [13].

#### k. Other

##### (1) Moon

The red light brightness of large areas of the surface of the moon may be strongly affected by variations in corpuscular solar radiation as a consequence of fluorescence of the rocks [43, 43a]. There have also been reports of very localized, temporary brightenings and/or flushes or color (generally pinkish or reddish, but occasionally greenish or bluish) at various locations on the lunar surface. The craters Eratosthenes [5] and Aristarchus [52] have been mentioned in the past as sites of various phenomena. Recently the areas around the craters Kepler [43] and Aristarchus [36, 60] have received attention. Although these smaller scale brightenings may be related to conditions which originate on the moon itself the larger scale brightenings may be due to solar flare emissions [43a]. If this hypothesis is true, then similar events should increase in frequency.

as the next solar maximum approaches. As yet there is not enough data to provide more than a tentative correlation.

## (2) Comets

Variations in the brightness of comets may be produced by solar activity. It is fairly certain that observed variations in the tail structure of comets, on their approach sunward, are due to interactions with the solar wind [1].

## (3) Quasars

Quasi-stellar radio sources, sometimes called quasars, are about 100 times brighter than a typical galaxy but are only about a fifth to a hundredth of its diameter. Only about 10 are now well established. They all are powerful radio emitters, and one of them, the object designated as 3C 147, is the most distant object now known [37]. Because of unexplained fluctuations in the brightness of quasars there has been some discussion of quasars being much closer to earth than first thought and of sizes only light-days across [65]. More rapid fluctuations of as much as 60 percent in one or two seconds were first noticed by radio astronomers of the University of Cambridge. These fluctuations are apparently caused by the solar wind which creates turbulence in interplanetary space similar to the turbulence in the atmosphere which causes stars to twinkle. Thus the quasars seem to twinkle. A. Hewish, P.F. Scott and D. Will, of Cambridge have advanced this hypothesis in a recent issue of Nature [40].

## (4) Television and Radio

Television signals normally propagate in straight lines through the ionosphere, because the frequencies are well above the critical frequencies for reflection. However, there have been cases of anomalous propagation of TV signals over long distances (beyond the horizon) during periods of enhanced ultraviolet and X-ray radiation, demonstrating that reflection had occurred. This effect is termed "ducting" [7, 33].

Anomalous propagation of radio signals also occurs during periods of enhanced solar radiation. However, the effects are dependent upon the frequency of the radio signals. Radio propagation is a science in itself and it is not the purpose of this pamphlet to delve too deeply into it. Some effects of solar radiation upon radio propagation have already been mentioned in previous sections, i.e. SEA, SWF, and SPA, and will not be discussed further.



## 7. Observation techniques

This section contains only a few comments on a very large subject, and is intended only to give the reader a little feeling for the problems involved as well as some of the instruments employed in observing the sun and its effects.

Some observations of solar phenomena must be made indirectly while others are made directly. Unfortunately the largest body of our knowledge is based upon indirect observations. Based upon these observations, various solar models are devised. Measurements are made of model parameters which are related by known laws, then assumptions are made about values of unobtainable terms. If this description of the structure of solar knowledge leaves the reader with a sense of dissatisfaction, that is one purpose of this pamphlet. Needless to say, every piece of information is necessary if at some time a theory is to be derived which will eventually explain all facts of the data. Considering the difficulties involved in measuring solar parameters, it is more remarkable that a constructive unanimity exists than that there are disagreements and uncertainties in the data. The results of indirect methods of measurements lead to numerous inconsistencies between authors and to frequent changes in proposed values for such parameters as temperature and density of the various solar features and in the proposed theories for their formation.

Direct observations, however, are less subject to argument if sufficient care is taken in obtaining them. The explanations of the various features may be argued over, but the observations themselves have been known to stand for centuries until finally the correct explanations are made. The following discussion will concern itself with some of the types of observations being made of solar phenomena and the instruments being used to make them.

### a. White (i.e., visible) light observations.

Since the time of Galileo solar phenomena have been observed and recorded. From 1610 to the beginning of 1613, the English observer, Thomas Harriot (1560-1621), made some 200 observations of sunspots, and was the first to draw them [10]. From this time until the late 1800's the only observations of the sun were by white light. Telescopic observations disclosed to various dedicated observers the rotation rate of the sun, the fact that the solar axis is inclined to the ecliptic, the solar 11-year cycle, etc. Although solar spectroscopic studies first began in the mid 1800's telescopic observations in visible light have continued to produce

useful and necessary information.

As late as the early 1900's solar phenomena were still being observed with fairly small telescopes. Now, however, the equipment of solar observers has become so bulky and complicated that a system of moveable mirrors with a fixed telescope has come into use. The mirror array of this system is called the coelostat. Fig 14 is a diagrammatic sketch of such an array. Plate XXII is an example of a coelostat used at the Sacramento Peak Observatory, Sunspot, New Mexico. In Figure 14, the lower mirror has a rotation rate of one revolution in 48 hours.

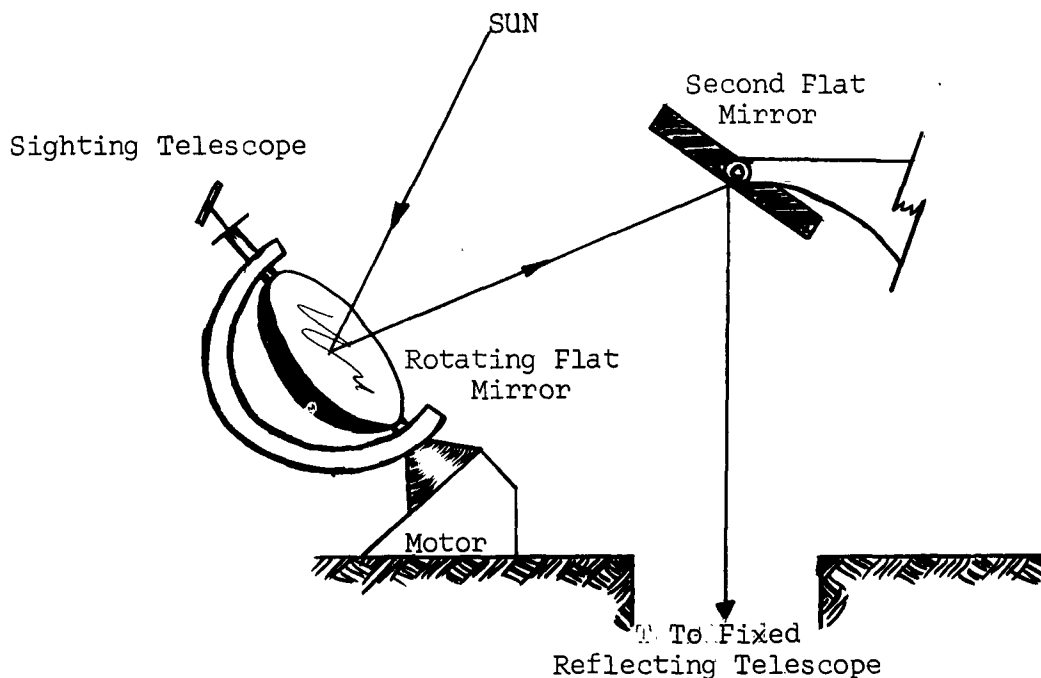


Figure 14. COELOSTAT

Since the reflected beam turns through twice the angle of the mirror, the mirror always reflects the light of the sun to the second flat mirror. The second flat reflects this light into the telescope.

Studies of the sun's image in white light are generally accomplished by photographic techniques or by projection methods. Direct visual observation of the white light image of the sun is impossible, if eye damage is to be avoided, without suitable filters due to the intense light.

## b. Monochromatic light

(1) Spectroscope and spectrograph. The spectroscope was first used in the mid 1800's to observe the sun's spectrum. About this time, the great German optician Fraunhofer observed about seven hundred dark lines crossing the solar spectrum. These lines have since been known as Fraunhofer lines. They occupy fixed places in the spectrum and are characteristic of specific substances under various degrees of ionization. More than 20,000 lines have now been identified in the portion of the solar spectrum that is recordable on the ground [33].

The spectroscope is an instrument for studying the spectrum visually. If it is arranged for photographing the spectrum, it is called a spectrograph. The older spectrographs used a prism. The light from the sun entered a slit which was a few thousandths of an inch wide, passed through a collimating lens which rendered the light parallel, then through a prism which dispersed the light according to its wavelength, and finally through an objective lens which focused the various wavelengths of light at different points on a photographic plate (see Figure 15). These prism spectrographs are now being largely

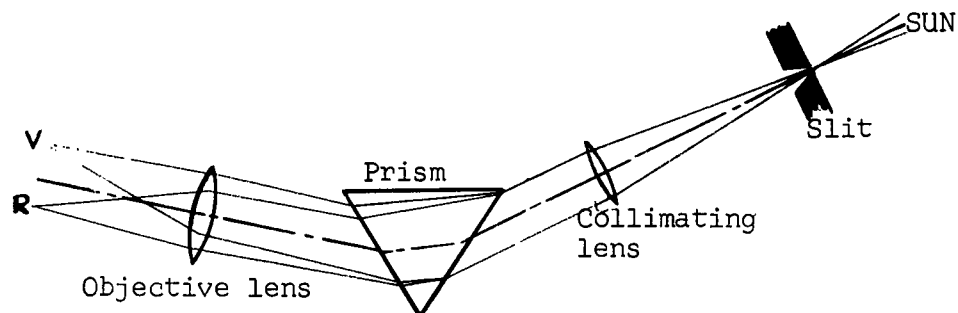


Figure 15. The Prism Spectroscope

replaced by diffraction gratings or blazed gratings because of the prohibitive costs of the larger prisms which must be used to obtain better resolving power.

The diffraction grating consists of a large number of equidistant parallel lines (about 15,000 lines per inch) which are ruled

very accurately upon some highly reflecting substance (such as glass or speculum metal). When white light strikes the grating it is diffracted according to wavelength. The greater the diffraction angle the less intense, but more detailed is the spectrum. The grating produces several partially overlapping spectra instead of a single spectrum, so to remedy this situation (as well as the weakness of the spectra), blazed gratings have been introduced. Blazed gratings are so ruled that the reflected light is concentrated into a few or even a single order of the spectrum. Because of this ability to concentrate the light, blazed gratings are being incorporated into most of the newer instruments of this type.

To further improve the resolving power of spectrographs, interferometers may be used. These instruments yield a very good definition of small regions of the spectrum---for instance, around a specific Fraunhofer line or bright emission line of the spectrum. Improvements have also been made by placing the entire spectrograph in an evacuated chamber. This reduces the effects of atmospheric turbulence along the instrumental light path, thus steadying the spectral image.

(2) Spectroheliograph and Spectroheliograph. The spectroheliograph is an instrument which allows an observer to view the sun in the light of a very narrow spectral band of wavelengths. The principle of the spectroheliograph was discovered almost simultaneously about 1890 by Hale and Delandres [7]. Whereas an observer can only view the photosphere of the sun through a visible light telescope, the spectroheliograph allows one to view higher layers of the solar atmosphere.

The light from the photosphere passes unweakened through higher layers of the solar atmosphere except for certain wavelengths which are absorbed to give rise to the Fraunhofer lines described previously. The absorption is not complete, however, so an instrument capable of viewing the solar spectrum only in the wavelengths of the Fraunhofer lines would enable an observer to view the layer of the solar atmosphere in which a certain wavelength was absorbed. This instrument is the spectroheliograph. The spectroheliograph can, of course, be arranged to photograph the sun in these various wavelengths, and when such an arrangement is made, the instrument becomes a spectroheliograph. The photographs themselves are then spectroheliograms, just as the photograph of a spectrum is a spectrogram.

The spectroheliograph (see Figure 16) consists of a lens,  $L_1$ , which focuses an image of the sun upon a slit,  $S_1$ . The light then passes through a collimating lens,  $L_2$ , and falls upon a grating,  $G$  (very few modern spectroheliographs use prisms instead of gratings).

Then, depending upon the optics used in the system, the light is thrown by some method upon a second slit,  $S_2$ , which selects the desired viewing wavelengths from the rest of the spectrum. If the entire spectrograph is moved so that  $S_1$  passes across the fixed image of the sun and  $S_2$  across a photographic plate,  $P$ , the resulting photograph will be taken in the light of the selected wavelength only. In a spectrohelioscope, the slits are set into rapid oscillation so that the entire solar disk may be seen in the selected wavelength's light. Moving pictures may also be taken of the sun. The instrumental set-up which does this is called a spectroheliocinematoscope.

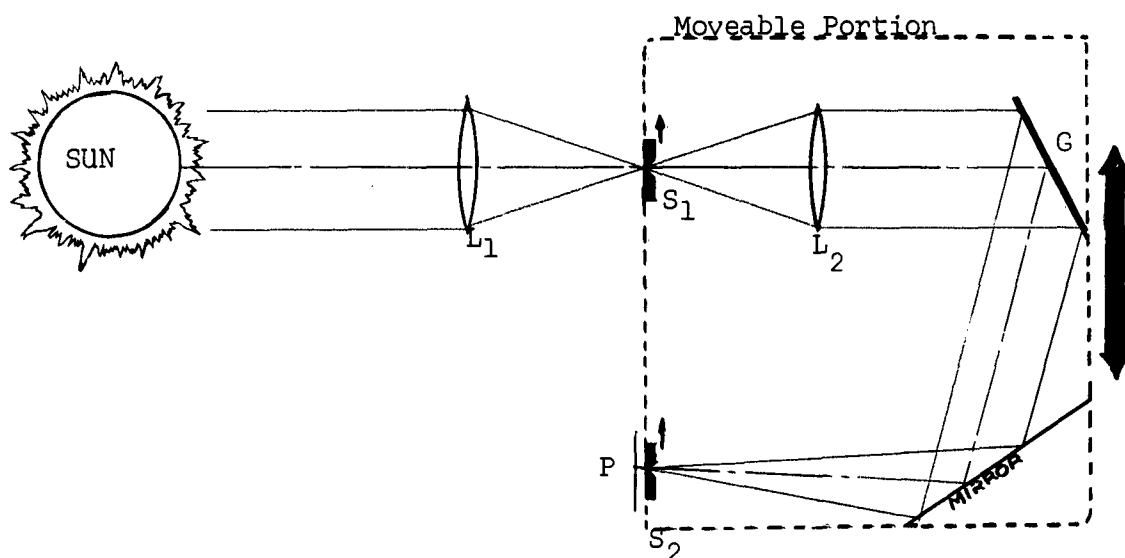


Figure 16. Spectroheliograph

The spectroheliograph is used most commonly to photograph the sun in the dark Fraunhofer absorption lines of calcium and hydrogen - specifically the H and K lines of calcium and the Balmer  $\alpha$  line of hydrogen. Other lines, such as the D-3 line of helium, are photographed for special purposes.

(3) Narrow Bandpass Filters. In contrast to instruments which spread the light of the sun into a spectrum and then select a certain portion for viewing or photographing, the narrow bandpass filters filter out all light except the design wavelength which was

chosen for inspection. These filters are usually much less costly and bulky and much simpler than the usual instruments for solar research, but they are fairly limited and critical in operating range. Because of these characteristics they have been largely used for routine solar patrol work in the last few years. One of the more reliable and rugged types of these instruments is the birefringent interference filter designed by Lyot and independently by Ohman. The Lyot filter consists of several biaxial quartz disks, graduated in thickness and separated by spar spacers. The quartz and spar crystals essentially remove unwanted wavelengths by polarization and absorption, allowing only the selected wavelength to pass through the filter. The Lyot filter is almost exclusively used to view the sun in the light of the Balmer alpha absorption line of hydrogen ( $H-\alpha$ ). Imbedded in the instrument is a thermal control which keeps the instrument centered on the  $H-\alpha$  line and which may be used to vary the viewing wavelength slightly either to the red or violet side of the center of the line.

c. Coronagraph. The coronagraph was first invented by Bernard Lyot and was a milestone in solar astronomy. Before its invention, solar astronomers had to wait for total eclipses of the sun in order to study the solar corona, and even then, frequently had to travel, transporting much equipment to various isolated portions of the world. The coronagraph now enables solar astronomers to observe the inner corona without an eclipse by instrumentally causing an artificial eclipse of the solar disk with an occulting disk. It also enables observation of solar limb prominences in monochromatic light (see Plate IX).

The principle of the coronagraph is very simple (see Figure 17). The light from the sun is collected by an objective lens  $L_1$ , made of a special highly polished glass which is selected for freedom from internal blemishes. The image of the sun is then focused upon a reflecting cone, C, which intercepts the direct light of the solar disk, allowing the corona to be seen. The light then passes through a collimating lens,  $L_2$ ,

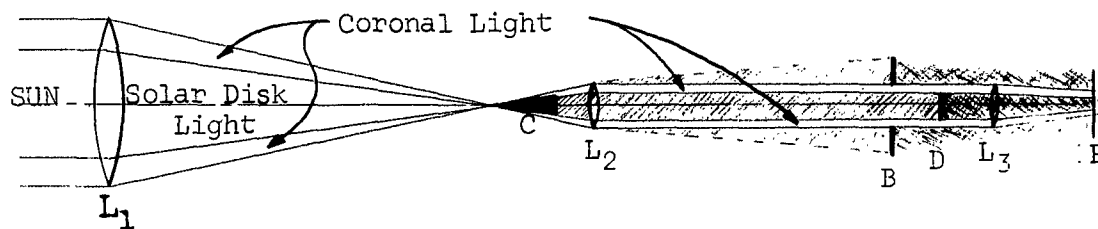
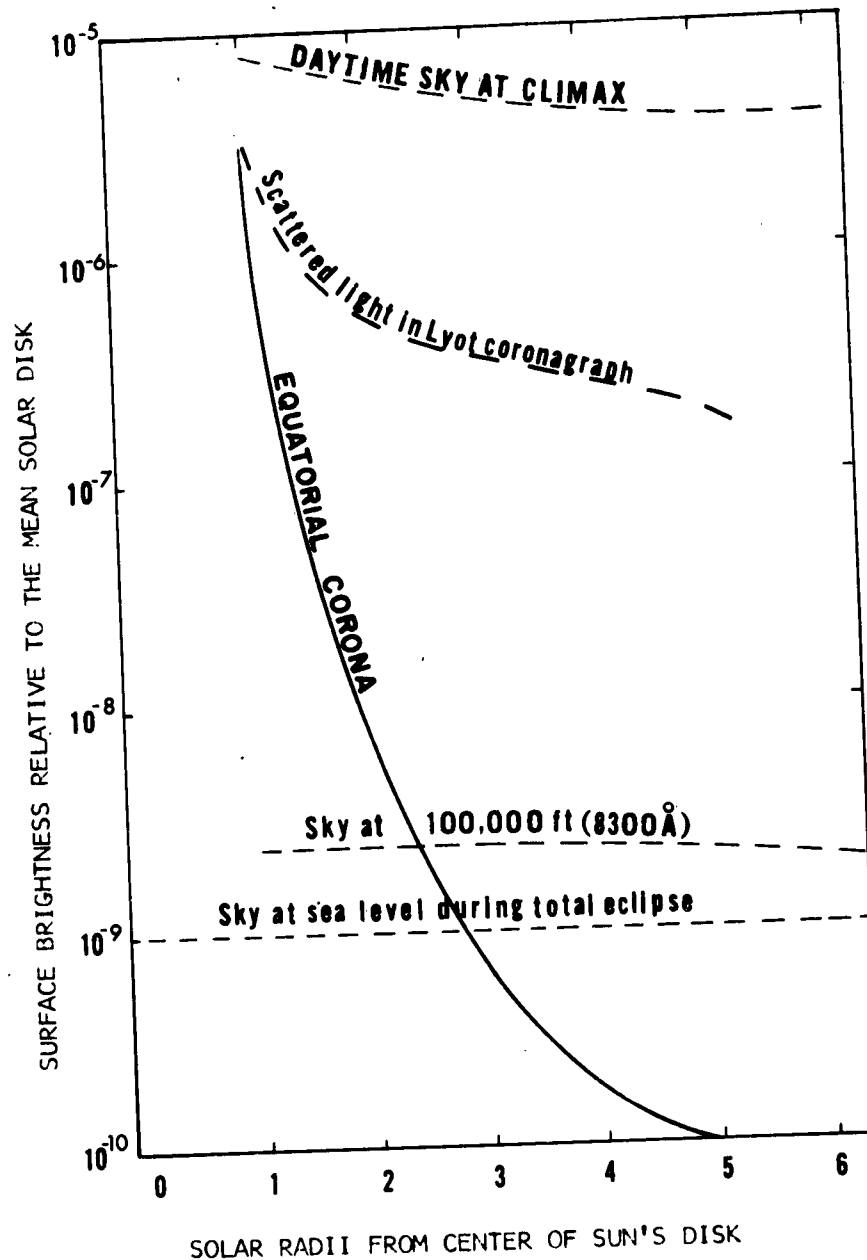


Figure 17. The Coronagraph

and falls upon various baffles, such as B and D, which intercept the scattered light from various double reflections in the lenses. The occulted image of the sun surrounded by its coronal halo is then focused upon a photographic plate, P, by the lens,  $L_3$ .

The coronagraph allows the inner corona to be seen without an eclipse, but until recently, the outer corona was invisible except during eclipses. This has been true because of scattered light, both in the coronagraph itself and in the daytime sky. Figure 18, compares several terrestrial sources of interference with the solar equatorial corona's surface brightness during sunspot minimum [55]. It should be noted that the scattered light in the coronagraph itself is brighter than the corona. Thus auxiliary equipment is usually used with the coronagraph to enable the inner corona to be studied, such as mentioned in Sections 7b(1) and 8b(3), above. Recently, much improved coronascopes have been lifted to high altitudes by balloons [55]. These instruments have enabled the solar corona to be viewed out to about five solar radii. Figure 19 depicts schematically the instrument, Coronascope II, which was flown at an altitude of 99,000 feet on 5 March 1964, for over six hours of solar coronal observing.



**FIGURE 18. COMPARISON OF THE BRIGHTNESS OF SCATTERED LIGHT WITH THAT OF THE SOLAR CORONA. (ADAPTED FROM REFERENCE 55)**



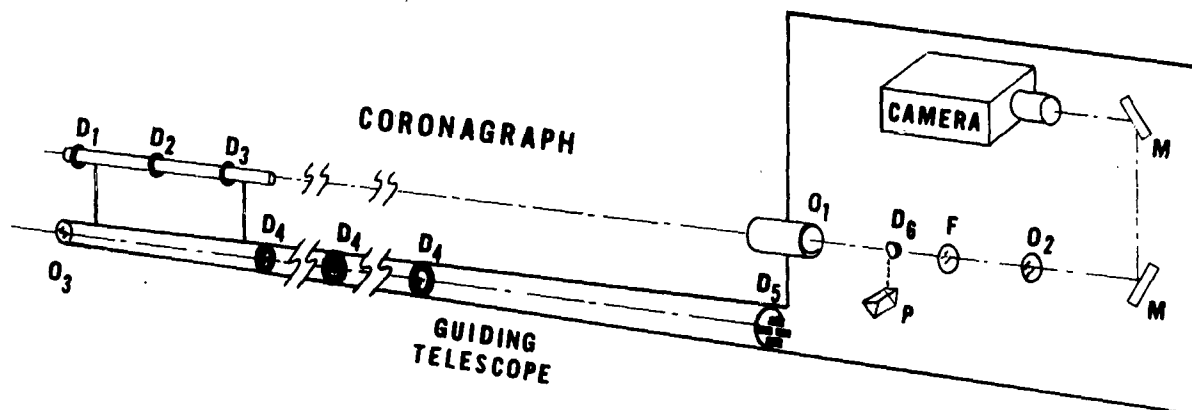


Figure 19. Coronascope II.  $D_1$ ,  $D_2$ , and  $D_3$  are external occulting disks for the primary objective lens,  $O_1$ .  $O_3$  is the objective lens of the guiding telescope. The  $D_4$ 's are vignetting disks to reduce interior scattered light. At  $D_5$  are the guiding telescope's occulting disk and photocells.  $D_6$  is the coronascope's occulting disk and  $P$  is a prismatic light trap.  $F$  is the field lens and  $O_2$  is the secondary objective lens which, with mirrors,  $M$ , constitutes the final optical portion of Coronascope II. (Adapted from [55]).

d. Magnetograph. The magnetograph is a very complicated instrument which incorporates a photoelectric detector to measure very small deflections in certain lines of the solar spectrum. These deflections are caused by the effect of weak magnetic fields on the sun. The instrument scans across the solar disk, recording the deflections which are a measure of the intensity of the magnetic field of the solar area being scanned. These instruments can measure weak magnetic fields with a degree of accuracy far exceeding the classical photographic or visual methods [55].

Recently J. W. Harvey at the Lockheed Solar Observatory has applied a photographic technique suggested by Giovanelli to detect local magnetic fields as weak as 100 gauss. Since  $H\text{-}\alpha$  light is thought to originate in a magnetic field parallel to the line of sight, the  $H\text{-}\alpha$  spectrum

line wings should be partially circularly polarized. The technique passes the sun's light through a quarter wave plate in front of a birefringent filter with the plate tuned to the steepest part of the H- $\alpha$  line wings. Two photos are taken in quick succession, one with the plate orientated to block left hand circularly polarized light and the other right hand light. A composite photo is then made by combining the negative of one photo with the positive of the other. In this photo, one polarity produces dark area and the other white areas; the degree of darkness or whiteness indicating the magnetic field strength [39].

e. Radio. The real discovery of solar radiation in the radio wavelengths was made in 1942 by British radar operators. Since World War II, the scientific discipline of radio astronomy has taken giant strides and has become an entire subject in itself. Since the subject is so extensive this pamphlet can only give the reader an idea of the types of radio observations and instruments which are used to study the sun. More detailed information may be found in the various texts and references on radio astronomy, solar astronomy and the like; for example, references [1, 5, 7, 11, 12, 19, 63, 68]. The various types of solar radio emission have already been discussed in Section 5 and will not be described further.

Radio telescopes have been mentioned in previous sections. Although the resolution and usefulness to solar radio astronomy of the various telescopes in use today vary depending on the sizes of the antenna reflectors and the wavelengths being used, all of the telescopes operate on the same principle. The telescope consists of two parts, the antenna and the receiver. All radio astronomical telescopes are directive and usually incorporate a reflector to focus the energy being received upon the antenna feed horn. The antenna then feeds the energy to the receiver which consists of an amplifier plus detector. Thus the radio telescope is essentially a very sophisticated radio reception system with a high degree of directivity. Plate XIX depicts the essential parts of a typical, steerable radio antenna. The principles of interferometry have also been adopted by radio astronomy. This technique for increasing resolution requires two or more antennas. Over the past 20 years, many radio telescopes have been built which use the interferometry technique. An excellent discussion and description of the techniques of this subject may be found in a recent text [12] if the reader desires more detailed information.

f. Comments. There are variations in observations of solar features in the visual range due to such factors as foreshortening at the limb, for which only a partial correction can be made, and differences in the observed starting time of flares. Systematic

differences between observatories are caused by differences in elevation and "seeing" conditions. For an unknown reason, which is probably not physical, a larger number of sunspots are observed on the eastern hemisphere of the sun. Measurements of the velocity of prominences and radio sources are obtained from Doppler shifts of the spectral lines in which they are observed.

Most of the shorter wavelengths of the electromagnetic spectrum, particularly X-rays and ultraviolet, and nearly all corpuscular radiation, are absorbed by the upper atmosphere and can be observed only by high altitude vehicles. While rapid advances are being made, observations are limited in their coverage, of space and time. Until recently, the properties and even the existence of the solar wind were only conjecture. Even now it will be a long time before the interplanetary field, which affects the paths of high energy particles in space, is completely mapped and described. A better understanding of the physical processes which relate the observed features, and standardized units of measurement which relate to physical causes rather than to appearance alone are greatly needed.

## 8. Solar Prediction.

In its present state of development, solar prediction is limited to anticipation of the time and location of solar flares and the occurrence of radio noise storms. Ideally, the art should include the selection of those flares which will produce a large increase in solar cosmic radiation in a given sector of space. In substance, the art now permits the identification of times and places where flares may occur, and of periods when flares will probably not occur, but does not permit separation of the "may" from the "will". Few important flares occur during periods when they are not anticipated; on the other hand, during years of solar maximum the indicators of flares are present continually.

### a. Correlations

(1) The major (3+) cosmic ray flares or proton events have little or no correlation with the solar cycle, i.e., they have no particular tendency to occur during the maximum period. However, they tend to occur most frequently during both the increasing and the decreasing portions of the solar cycle. In all known cases of a cosmic ray flare, the flare eventually covered a significant portion of the umbra of a sunspot. On the other hand, the reverse is not true. There have been large flares which did cover significant portions of the umbrae of sunspots but did not cause a cosmic ray event at the earth. The reason for this could be that the stream of protons simply missed the earth. However, in all cases of flares covering umbrae, Type IV radio emission has been noted. This is another puzzling fact of solar

physics since if protons were produced they should have been detected along with the Type IV radio emission.

(2) Some correlation is indicated between cosmic ray flares and continuum radio bursts (Type IV). All cosmic ray flares have been accompanied by Type IV radio emission. However, the reverse is not true. As mentioned above, Type IV radio emission has been detected when protons have not.

(3) There is little correlation between wide band H- $\alpha$  emission in the development phase, or a rapid rise to maximum, and cosmic ray events.

(4) 86% of recent flares which have produced great magnetic storms have occurred in the northern solar hemisphere [45]; however, there is reason to believe this trend will reverse in a later epoch.

(5) All proton events (from cosmic ray flares) on earth have come from flares which have shown loop type prominence activity. Again, however, the reverse is not true. It is true, nevertheless, that loop type prominences are indicators of flare areas although they cannot indicate the importance of the flares.

b. Indices which presage flares:

(1) Large, complex sunspot group.

(2) Rapid increase in the size of a sunspot group.

(3) Large penumbra around a sunspot.

(4) Bright, complex plage.

(5) Rapidly developing plage.

(6) Persistent plage. Most cosmic ray flares occur on the second rotation of a plage, but a few occur as late as the 8th rotation. No major cosmic ray flare has ever occurred during the first rotation.

(7) Complex magnetic structure in a sunspot group. Flares tend to break out at the neutral points of fields having complex polarity, where the neutral point is surrounded by a high field gradient. Flare intensity may be proportional to the gradient.

(8) A large flare is usually preceded by many small flares in the same region.

(9) Advance warning of an active region about to rise over the east limb may be inferred from the period of solar rotation, or the appearance of loop prominences on the limb, or an intensification of the coronal green line (5303 Å) activity.

(10) Enhanced radio emission; high-amplitude, long-duration emission at 10.7 cm, and Type III bursts.

(11) Increase in loop prominences and surges.

(12) Hot spots in the corona, with emission in the yellow line of Calcium XV.

c. Indices of flare location related to the Mount Wilson classification of sunspot groups (Section 3b(1)).

When Mt. Wilson Type (b) and (c) regions are present, there is a strong tendency for flares to occur in a (c) region. With (a) and (b) present, there is a small preference for the (a) region. With (a) and (c) present, flares occur at the boundary between polarities; however, the boundary between two (b) regions of opposite polarity is not favored. In  $\beta$  groups, flaring surrounds the spot clusters rather than the boundaries. Alpha groups are often surrounded by flares unless a (c) group is present. Production of large flares is greatest for  $\gamma$  groups in which the magnetic classification remains unchanged during disk passage. Cosmic ray flares, which are all of Importance 3+, usually originate in  $\gamma$  or  $\beta\gamma$  groups, and cover significant portions of the umbra of the spot near which they originate.

d. Indices of flare location quoted from Severenyi [62]:

"1. Virtually all flares or basic flare foci occur at the neutral points of magnetic fields of groups exhibiting complex polarity at the instant of flare appearance, and in individual cases they occur on closed neutral lines."

"2. The bright filaments and clouds which form in the development of flares are frequently situated along, or parallel to, the neutral lines."

"3. Intensity of a flare may be proportional to the strength of the magnetic gradient surrounding the neutral point."

e. Discussion

Present forecasting capability is fairly adequate for preventing losses due to solar flare radiation during solar minimum. Anderson's

analysis, using penumbral area, can be used to avoid about 2/3 of dangerous radiation encounters on 4- and 7- day excursions into space. However, during solar maximum, present prediction techniques will become inadequate because they would result in forecasts of almost continuous hazardous conditions, whereas such conditions will in fact occur only a small portion of the time.

Pioneer efforts were made by NASA and the Sacramento Peak Observatory of the Air Force Cambridge Research Laboratories to learn how to predict solar activity. In 1963, the Air Weather Service had been conducting an experiment which exhibited some skill in solar prediction. At that time, the experiment was changed to an operational function which began to deliver daily solar forecasts five days a week. Since that time, the Air Weather Service has successfully forecast hazardous conditions 70% of the time when they actually occurred; a high percentage of the time, dangerous flares were forecasted but did not occur [24] .

The daily solar forecasts made by the Air Weather Service provide:

- (1) The daily solar activity and magnetic and radio fluxes,
- (2) probability forecasts of solar flares of Importance two or greater and proton events, and numerical forecasts of magnetic and radio activity, and when pertinent,
- (3) radio propagation effects.

To sum up the prediction problem, long-range (i.e., periods of years or more) and medium range forecasts (i.e., periods up to a month or so) can be discussed separately. Long-range predictions may be made based upon the cyclic activity of the sun. For instance, 1968 will be a year of high solar activity since this will be near the peak of the present (20th) cycle which began in the latter part of 1964. According to Figure 5, the last cycle was near the peak of a hypothetical 90-100 year cycle. With this fact in mind, the big question is whether the 1968 maximum will be very much less active than the 1957-58 maximum or still more active. Some idea of the answer can usually be obtained by noting how rapidly the activity level rises from the minimum. Usually, the more rapid is the early rise from minimum, the greater will be the activity level of the cycle.

Medium range forecasts may be made by using the 27 day rotation period of the sun plus information on the life history of an active region. Of course, both the long and medium range forecasts must be

phrased in rather general terms because of the uncertainties involved. If all factors indicate the absence of activity, forecasts of this situation can be made with some confidence. However, if active conditions are indicated, there is usually no way of determining just when it will occur or what the level of activity will be. The forecasts can be refined with greater certainty depending on the number of indices present. Most of the indices tabulated in Section 8.b. are more useful for short-range (hours to days) forecasts than medium or long-range forecasts. However, the longer an index exists without a flare occurring, the greater the probability grows that a flare will occur (that is until the index disappears).

#### f. Requirements

Despite the problems of forecasting solar activity, efforts to better forecasting techniques are continuing. Development of techniques is hampered by lack of homogeneity in solar observations. Reasons for this are that the indices in use do not adequately describe solar phenomena, that observation practices differ, and that there are large variations in the appearance of solar phenomena depending on location and elevation of the observatory. When better indices of solar activity are developed, a new period of record may have to be accumulated using these indices. An improved communications network for collecting observations is a requirement for close monitoring.

Most of the more sophisticated observations are indirect, necessarily requiring important postulates which cannot be verified at the present time. In order to predict important solar events before they happen, it will probably be necessary to develop a much better understanding of the physical processes which cause the events. Radiation from solar events travels outward into space guided by lines of magnetic force which determine whether or not the radiation will intercept the earth. Extensive observations of the interplanetary field, followed by forecasts of its future configuration, will probably be needed as inputs to successful forecasts of the terrestrial and space effects of solar radiation.

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